PB81-173064

United States - Canada Memorandum of Intent on Transboundary Air Pollution. Atmospheric Modeling, Work Group 2 Interim Report

(U.S.) Environmental Protection Agency
Washington, DC

11 Mar 81

U.S. Department of Commerce
National Technical Information Service
NTIS

TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO. PB81-173064
4. TITLE AND SUBTITLE US-Canada Transboundary Air Pollution Work Group 2 Interim Report on Strategies and Implementation.		5. REPORT DATE March 11, 1981
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S)		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS EPA Office of International Activities (OIA) Washington, DC 20460		10. PROGRAM ELEMENT NO.
		11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS Environmental Protection Agency Washington, DC 20460		13. TYPE OF REPORT AND PERIOD COVERED Interim 8/80 - 3/81
		14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES
One in series of reports on transboundary air pollution prepared jointly by US and Canadian Governments

16. ABSTRACT

This is an Interim Report prepared by a US/Canada Work Group in accordance with the Memorandum of Intent on Transboundary Air Pollution concluded between Canada and the United States on August 5, 1980.

This is one of a set of four reports which represent an initial effort to draw together currently available information on transboundary air pollution, with particular emphasis on acid deposition, and to develop a consernus on the nature of the problem and the measures available to deal with it. While these reportscontain some information and analyses that should be considered preliminary in nature, they accurately reflect the current state of knowledge on the issues considered. Any portion of these reports is subject to modification and refinement as peer reciew, further advances in scientific understanding, or the results of ongoing assessment studies become available.

Other Transboundary air pollution issues will also be included

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT Releasable to public	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES 180
	20. SECURITY CLASS *(This page)*	22. PRICE

EPA Form 2220-1 (9-73)

PB81-173064

UNITED STATES - CANADA

MEMORANDUM OF INTENT ON TRANSBOUNDARY AIR POLLUTION

PRODUCT OF:
NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA. 22161

ATMOSPHERIC MODELING

INTERIM REPORT
FEBRUARY 1981

ATMOSPHERIC MODELING

WORK GROUP 2

CO-CHAIRMAN

H. L. Ferguson, Canada
L. Machta, United States

PHASE I

December 19, 1980

(REVISED January 15, 1981)

Submitted to the Coordination Committee in Fulfillment of the Requirements of the Memorandum of Intent signed by United States and Canada on August 5, 1980.

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
ENVIRONMENTAL RESEARCH LABORATORIES

JAN 14 1981

D. L. Hawkins
Assistant Administrator
for Air, Noise and Radiation
U.S. Environmental Protection Agency
Washington, DC 20460

R. M. Robinson
Assistant Deputy Minister
Environmental Protection Service
Environment Canada
Ottawa, Ontario
Canada K1A 1C8

Dear Messrs. Hawkins and Robinson:

We are pleased to transmit under cover of this letter the final interim report of Work Group 2 (Atmospheric Modeling) as required by our terms of reference and work plan. We believe that this report satisfies, in a scientifically responsible manner, our Phase I objectives.

Sincerely,

Lowell Smith for

Lester Machta,
U.S. Chairman,
Work Group 2

Ferguson

Howard Ferguson
Canadian Chairman
Work Group 2

cc: S.E. Ahmad
E.G. Lee

10TH ANNIVERSARY 1970-1980
National Oceanic and Atmospheric Administration
A young agency with a historic
tradition of service to the Nation

This is an Interim Report prepared by a U.S./Canada Work Group in accordance with the Memorandum of Intent on Transboundary Air Pollution concluded between Canada and the United States on August 5, 1980.

This is one of a set of four reports which represent an initial effort to draw together currently available information on transboundary air pollution, with particular emphasis on acid deposition, and to develop a consensus on the nature of the problem and the measures available to deal with it. While these reports contain some information and analyses that should be considered preliminary in nature, they accurately reflect the current state of knowledge on the issues considered. Any portion of these reports is subject to modification and refinement as peer review, further advances in scientific understanding, or the results of ongoing assessment studies become available.

More complete reports on acid deposition are expected in mid 1981 and early 1982. Other transboundary air pollution issues will also be included in these reports.

SUMMARY

As outlined in the Memorandum of Intent, the Atmospheric Modeling Work Group was charged with describing the transport of air pollutants from their sources to final deposition, especially deposition in sensitive ecological areas. The first phase of the work has been completed with the submission of this report. The overall purpose of the report is to describe the development of state-of-the-art, source-receptor relationships based on available model results and measured deposition values from monitoring networks. Though this exercise is in a preliminary stage, it is believed that the activities of the Group have produced the best available information to guide transboundary air pollution control strategies in both countries.

Several models have been developed in both Canada and the U.S. which could be used for long-range transport studies. The Group decided to use only models that met certain criteria. In general, the models had to be fully operational, numerically practical, flexible enough to include new data and other such factors. Features of the individual models are reviewed in this report.

The long-range transport models selected for intercomparison in this report have several important features. These models use emission and meteorological data, and meteorological,

chemical and empirical parameters to calculate the transport of a given pollutant to a sensitive area. To date the models have been successful in describing sulfur deposition on an annual basis. Hydrogen and nitrate ion deposition, two important factors in acid rain, have not yet been successfully incorporated in the models. Initial source-receptor relationships for sulfur have been determined using model calculations.

If the models are to be useful to satisfy the requirements of the Memorandum of Intent, a quantitative relationship between pollution emissions and deposition in sensitive areas must be established. To do this, a transfer matrix approach has been adopted. Theoretically, by using this method, a change in a source strength can be tied to a change in the deposition amount of the given pollutant in a sensitive area. Preliminary transfer matrix results are discussed in this report, but these results are subject to future changes, possibly significant, as modeling techniques are refined. Though preliminary in nature, the report sets up the needed framework to produce a more accurate transfer matrix during Phase II.

In order to check the accuracy of the models, field measurements of the deposition from the existing monitoring networks in both countries are required. At present, wet deposition/acid rain is being measured reasonably well.

Dry deposition, an important factor in ecological effects, can not yet be measured on a routine basis. Existing deposition data will be used to evaluate the selected models utilized by the Group throughout its Phase II effort.

Though the long-range transport models do have restrictions on their usefulness, they are an important and possibly the only guide to establishing source receptor relationships. Their further development and intercomparison will be an ongoing activity of the Group in Phase II.

LIST OF CONTRIBUTORS

This Phase I report was prepared by members of Work Group 2 as listed below. Authors carried the primary responsibility for chapters and monitors provided writing and reviewing assistance. Reviewers provided comment on final draft sections. In all cases Canadian and U.S. Work Group members worked closely on the preparation of individual chapters and on the final construction of the complete report. Drs. L. Smith and D. M. Whelpdale were responsible for coordinating the preparation of the report.

Chapter	Title	Author(s)	Monitor(s)	Reviewer(s)
1	Introduction	D. Whelpdale L. Smith		P. Choquette J. Blanchard
2	The Role of Modeling in the Development of Emission Control Strategies	A. Venkatram	B. Niemann	P. Choquette R. Morris
3	Summary of Selected Models	B. Niemann J. Young	M. Olson J. Miller	G. Paulin K. Demerjian K. W. Yeh
4	Source Region and Sensitive Area Development and Transfer Matrix Operation	L. Smith B. Niemann	D. Whelpdale	G. Paulin B. Silverman K.W. Yeh
5	Source-Receptor Relationships	P. Altshuller P. Summers		P. Choquette R. Kane
6	Monitoring	J. Miller	D. Whelpdale	G. Paulin F. Burmann
7	Conclusions, Recommendations and Phase II Work	G. Van Volkenburgh J. Miller		

TABLE OF CONTENTS

Summary

List of Contributors

List of Figures

List of Tables

1. Introduction
2. The Role of Modeling in the Development of Emission Control Strategies
3. Summary of Selected Models
4. Source Region and Sensitive Area Development and Transfer Matrix Operation
5. Source - Receptor Relationships
6. Monitoring
7. Conclusions, Recommendations and Phase II Work

References

Appendices

1. Work Group 2 Terms of Reference and Additional Guidance
2. Membership of Work Group 2
3. Glossary of Terms
4. Inventory of Available Models
5. Descriptions of Selected Models
6. Source Region and Inventory Description
7. Matrix Operations
8. Transfer Matrices
9. Workshop Summary Reports

LIST OF FIGURES

		Page
Figure 4.1 :	Map of eastern North America showing the two sets of geographical regions used in Work Group 2 modeling. Light and heavy (solid in Canada; slashed in U.S.) lines outline regions used by U.S. and Canadian models, respectively. U.S. aggregate SURE grid regions are identified by 2 or 3 character alpha-numeric labels (light), with sensitive areas having 'SA' as the first 2 characters. Canadian-model source regions are identified by large numbers, in boxes in the U.S. and in circles in Canada, and sensitive areas are identified by small numbers in circles. (See Appendix 6.)	4-3
Figure 6.1 :	Mean annual hydrogen ion (H^+) deposition in precipitation for period 1976-1979 (mg m^{-2} y^{-1}). Deposition values are derived from mean pH and mean annual precipitation. Adapted from Wisniewski and Keitz (1980).	6-4
Figure 6.2 :	Wet deposition of sulfate (SO_4) in precipitation in eastern North America for 1977 (g S m^{-2} y^{-1}). Adapted from Galloway and Whelpdale (1980).	6-5

LIST OF TABLES

		Pag
Table 3.1 :	Regional model parameter values for eastern North America transport simulations.	3-8
Table 5.1 :	Total annual sulfur deposition as computed from the ASTRAP model.	5-3
Table 5.2:	Example of Transfer Matrix from Appendix 8. Total Annual Sulfur Deposition in kg $ha^{-1}yr^{-1}$ (Table A8-10).	5-5
Table 5.3 :	Comparison of the predicted annual wet deposition of sulfur (kgS $ha^{-1}yr^{-1}$) from selected LRT models compared to the measured values.	5-7
Table 6.1	Estimated annual wet deposition of hydrogen and sulfate ion to specified sensitive areas.	6-7
Table 7.1	Work Group 2 Activity Schedule (revised 12/19/80).	7-6

Chapter 1

INTRODUCTION

The Atmospheric Modeling Work Group was established under the Memorandum of Intent in order to provide information, based on cooperative atmospheric modeling and analysis of monitoring network and other data, which would lead to a further understanding of the transport of air pollutants between source regions and sensitive areas. In addition, the Group was to prepare proposals for the "Research, Modeling and Monitoring" element of an agreement. The Terms of Reference of the Group and Work Group membership are contained in Appendices 1 and 2, respectively.

The purpose of this Phase I report is to provide as complete a response as possible to all the scientific and technical areas identified in the Terms of Reference and as specified in its approved work plan. During Phase I the Work Group has devoted its efforts to:

(1) Preparing a work plan for the first two phases;

(2) Identifying required inputs from and outputs to other Work Goups;

(3) Developing data bases and analytical methods which will be required in subsequent work;

(4) Developing preliminary source-receptor relationships based on available modeling results which can be utilized in Phase II by other Work Groups; and

(5) Developing a glossary of terms which all Work Groups can use (see Appendix 3).

During Phase II, the Work Group will:

(1) Endeavor to evaluate several selected models against available monitoring data sets and to intercompare further these models and their results with one another;

(2) Review the science of atmospheric transport and deposition of pollution in order to understand better the applicability and limitation of available models to predict the response in ambient pollutant concentrations and deposition rates to changes in emission rates; and

(3) Review and improve the source-receptor relationships to be used in the Phase III Work Group effort.

In this regard it is expected that some revision of designated sensitive areas and source areas to be used following Phase II will be accomplished by the appropriate Work Groups during Phase II.

Many advances in understanding the regional and long-range transport of air pollutants have been gained in recent years, in large part due to an expansion of basic research efforts coupled with the development and use of large mathematical models to integrate available scientific information. Even so, it is not possible to describe fully all aspects of air pollution transport on a regional or continental scale. Consequently, many simplifications have been made in the analyses of results presented in this report. A major effort will be made during Phase II to review available research results, both published and unpublished, in order to specify more precisely the validity and range of uncertainty that characterize the methodologies utilized and results presented in this and subsequent reports.

Although many substances may undergo transboundary atmospheric transport and have harmful effects upon either the atmosphere or surface receptors, acid deposition is the phenomenon of primary concern for the first two phases of our Work Group activities. As a consequence, highest priority has been given to the study of oxides of sulfur and nitrogen, the main precursors of acid precipitation. During this first phase, emphasis has also been placed on the development of the "transfer matrix" concept. It is this application of establishing quantitative relationships between sources and sensitive receptors for which mathematical models are uniquely suited, and the development of useful, comprehensible display of this information is of great importance.

This first report is structured to follow closely the terms of reference for the Group. The following two chapters describe the role of models in the particular application at hand, and those models which have been selected for use in Canada and the United States. In Chapter 4 source region and sensitive area development and the source-receptor matrix concept are presented. The fifth chapter, perhaps the most important of this Phase I report, presents source-receptor matrices from the five models for a variety of concentration and deposition parameters. Although these results are of a preliminary nature, they provide a good indication of the values and limitations of the approach, as well as some first estimates of the relative importance of various source regions. Chapter 5 will form the basis for refinements in Phase II, and for the work of Work Groups 3A and 3B. Chapter 6 is a brief survey of available field data, which provide valuable comparisons for the modeling results. The final chapter of this report, "Conclusions, Recommendations, and Work Plan", is of a preliminary nature, but does chart the future course of action of the Work Group. It is intended that the Phase II report will primarily be an elaboration upon this Phase I report; for this reason the report structure will remain the same, with upgrading of information and additions being made as necessary.

A large amount of reference material is available for the modeling work described in this report. This work draws heavily upon what was accomplished in the Canada-United States Research Consultation Group on the Long Range Transport of Air Pollutants as described in their recent reports.* Complete documentation of the models used herein is available, as are references to much other modeling work underway at the present time.

---

* Altshuller, A.P. and McBean, G.A., 1980. Second report of the United States-Canada Research Consultation Group on the Long-Range Transport of Air Pollutants. U.S. State Department, Canada Department of External Affairs, November 1980, 40 pp.

Smith. L.F. and Whelpdale, D.M., 1980. Atmospheric Transport and Deposition Modeling· Inventory, Analysis and Recommendations. Report to the United States - Canada Research Consultation Group on LRTAP. December 1980, 123 pp.

These two reports can be obtained from:

LPO Office,
Atmospheric Environment Service
4905 Dufferin Street
Downsview, Ontario, Canada M3H5T4

Program Integration and Policy Staff, RD-681
U. S. Environmental Protection Agency
Washington, D. C. 20460

Chapter 2

THE ROLE OF MODELING IN THE DEVELOPMENT OF EMISSION CONTROL STRATEGIES

Goals

Work Group 2 will provide several major output products to Groups 3A and 3B. One of these, a review of experimentally observed atmospheric loadings for hydrogen and sulfate ion, is discussed in Chapter 6 of this report. These loadings will be used by Group 3B as the starting point for planning strategies to reduce loadings in sensitive areas. A second major output is the transfer matrices (i.e., source-receptor relationships) for acid-deposition-related species. These matrices will be the major tool which Groups 3A and 3B will employ to develop strategies for the control of acid deposition species and precursors. Chapters 2 through 5 of this report discuss the development of these matrices in some detail in order that the present and future utility of this tool is well understood.

What is a Long Range Transport Model

Before introducing the concept of a transfer matrix, the concept of modeling in general will be reviewed.

A model is essentially a description of physical or chemical processes in the language of mathematics. Relationships between the variables of the system being modeled are replaced by logical connections or equations in the mathematical model. The model can be used to study the complex cause-effect relationships by well defined rules of mathematics. The long-range transport (LRT) model is a combination of submodels of the physical and chemical processes involved in long-range transport of various species under consideration. In order to keep the computing effort manageable, the submodels of a LRT model are often simplified by parameterization. This means that the LRT model may not reflect the degree of understanding we actually have of long-range transport. However, it is generally believed that the errors introduced by parameterization are not significant when the model outputs are averaged over time scales of the order of several months.

The basic components of a LRT model are

(1) A submodel for the transport of pollutants;

(2) A submodel for the chemical transformations of the pollutants to other (secondary) pollutants; and

(3) A submodel for the wet and dry removal of primary and secondary pollutants as they are transported.

The main inputs to an LRT model are

(1) Emission inventory of pollutants;

(2) Meteorological data such as wind speed, precipitation, boundary layer height and solar radiation;

(3) Ground cover data on the region of interest. This data might include variables such as surface roughness,

vegetative cover, type of surface (land, water), etc.; and

(4) Parameter values.

The precise nature of the input data requirements is a function of the complexity of the long-range transport model and its application.

The main uses and advantages of LRT models include the following:

(1) A model is a vital component of data interpretation. For example, parameters such as the oxidation rate of SO_2 to particulate-sulfate material can be inferred by fitting model results to measurements.

(2) A model can be used to interpolate between monitored observation points. This application is important in the computation of deposition over an area covered by a limited number of monitors.

(3) A model is an invaluable tool in the planning of large scale field experiments and in the design of monitoring networks. Sensitivity studies can be done to determine the relative importance of physical variables to be measured. Also, simulations can be used to estimate the optimal location of monitors.

(4) The computer simulation is the only way to estimate the relative contribution of many different source areas to the deposition at a receptor of interest.

For this last application, the contributions to the depositions or ambient concentrations at a series of receptor areas of interest from a series of specified source regions can be displayed conveniently in matrix form. This format of presentation is called a "transfer matrix" because each element of the matrix expresses, quantitatively, the physical relationship between a specified receptor area and a specified source area for the species and variable of interest. One can thus relate source to receptor, or "transfer" the effect of a change at source to the receptor. The matrix elements can be made independent of source strength, but they are functions of the chemical species, the variable chosen, and the averaging time used.

A transfer matrix is a convenient format in which to display changes in concentration or deposition patterns, corresponding to various emission reduction scenarios. Details of the use of the transfer matrix are given in Chapter 4. The impacts of emission reduction scenarios depend upon the formulation of the matrix, and the matrix in turn is only valid within the limitations of the LRT model used in its construction.

Present Limitations of LRT Models

Our incomplete understanding of the physical and chemical process involved in long-range transport as well as limitations on computing resources prevent us from constructing a "perfect" model. The necessary simplifications introduced into most available models will lead to errors in model outputs. Those areas in which simplifications are most likely to affect model results and which are currently being improved are

(1) The relationship between the H^+ ion and precursor sulfur compounds, especially SO_2;

(2) The characterization of the nitrogen-oxidants cycle in connection with H^+ ion; and

(3) The representation of the wet removal of pollutants via scavenging processes during rain or snow events.

The availability, accuracy and resolution of field measurements also limit both our ability to make reliable model predictions (when the data are used as model inputs) and our ability to assess the degree of uncertainty in model outputs (when the data are used for comparison purposes). In addition, the evaluation of model simulations of total and dry deposition are difficult because dry deposition cannot yet be measured reliably.

Typically, on an annual basis, model estimates and reliable field observations are expected to agree to within a factor of two. It is expected that this range of uncertainty will be narrowed in the future.

The above discussion points out the need for caution when using small differences in model results as a basis for choosing between alternate emission reduction scenarios. For example, a small percentage difference in the deposition contribution from two source regions could not be considered significant; similarly, a small percentage difference at the same receptor using different emission scenarios could not be considered significant.

Phase I Transfer Matrices

In Phases II and III, LRT model limitations will be critically analyzed in terms of current research, and it is expected that some limitations will be removed, and others quantitatively defined. While the "transfer matrices" given in this report must not be used as "final" in the strategy development exercise, it is the opinion of this Work Group that the present matrices can be used by Groups 3A and 3B to begin to consider the major elements of strategies which will alleviate excessive acid deposition. The present matrices can be considered to be qualitatively correct, based on evaluation work done to date by the various modeling groups. Only by having information (albeit qualitative) begin to flow among all the parties concerned in strategy development, can the entire process begin to function in an integrated fashion.

Chapter 3

SUMMARY OF SELECTED MODELS

Types of Models Available

There are two basic types of LRT Models: Lagrangian (trajectory) and Eulerian (grid).

A Lagrangian Model solves the conservation equations in a coordinate system fixed to each moving air parcel.

An Eulerian Model solves the conservation equations in a fixed coordinate system through which air masses are advected and diffused. The computation points are usually arranged in a fixed grid.

All models are then variations of these two basic approaches. One can have, for example, a statistical Lagrangian model or an analytical Eulerian model, the choice being made by the modeler to allow a certain form of output or to use a given form of input data.

The basic types of LRT models can be applied to both short-term (multi-day episodes) and long-term (monthly, seasonal, and annual) simulation periods, and outputs of both can be displayed as point values, areal values, or gridded values.

Work Group II decided that the annual time period should be the primary focus for modeling source-receptor relationships and fluxes for Phases I and II due to the large amount of preparatory work required to provide adequate shorter time period modeling results. A survey of modeling groups (see Appendix 4) revealed that there are about fifteen active modeling efforts in the U.S. and Canada and that the majority of the models are of the Lagrangian type and have been applied to monthly-to-annual time periods. The effort on Eulerian and episode type models has increased during the past year, providing more balance in the overall modeling effort.

Discussion of Models Selected

The models selected for this exercise fulfilled several important criteria, namely:

(1) They are fully operational;

(2) They are numerically practical;

(3) They can be expanded as the knowledge base increases;

(4) They can be used over the geographical and temporal time scales of interest; and

(5) They have each been at least partially evaluated through comparison with measurements.

Two regional air quality simulation models developed in Canada and three developed in the United States were selected for Phase I. It is conceivable that additional Canadian and/or U.S. developed models could be added to or replace this initial group of models as a result of the Phase II work effort. Appendices 4 and 5 summarize current North American modeling efforts and describe more fully those models used in Phase I analysis.

AES-LRT Model

The Atmospheric Environment Service of Canada (AES) has developed and applied a Lagrangian box model to simulate ambient concentrations and deposition patterns of sulfur throughout eastern North America (Olson et al., 1979). The AES-LRT model is based on trajectories, at approximately 600 meters above the surface, which are calculated from each designated receptor four times a day using analyzed winds on the standard numerical weather predicton grid covering North America. As the air parcels follow the trajectories towards the receptor points, sulfur dioxide emissions (1976-1980), mixing heights and precipitation amounts along the path are determined from gridded arrays. The transformation and deposition processes are parameterized linearly. The concentrations at each receptor are combined to form daily, monthly, and annual average concentrations and depositions. An evaluation of the model is being conducted using measured data from several American and Canadian networks for 1978.

OME-LRT Model

The Ontario Ministry of the Environment (OME) has developed and applied a simple statistical model to simulate long term ambient concentration and wet deposition patterns on a regional scale for eastern North America (Venkatram et al., 1980). The dispersion and removal of pollutants and the required meteorological parameters in the OME model are specified in terms of the statistics of these physical processes from wind and precipitation data. The source emission inventory corresponds to the year 1977. The OME model estimates compare quite favorably to measurements of annual wet deposition taken from Canadian and U.S. networks for 1977. The OME model also has been used to calculate the relative contribution from U.S. and Canadian SO_2 emission sources to the sulfur concentrations and wet deposition over eastern North America.

ENAMAP-1 Model

SRI International has developed a trajectory-type regional air quality simulation model (Bhumralkar et al., 1980). This model calculates monthly and annual average concentrations and dry and wet depositions of SO_2 and SO_4. The basic element of the ENAMAP-1 model is the emission of puffs of SO_2 at equal time intervals from all source areas. The puffs are assumed to be well mixed in the horizontal and vertical and to be transported by the mixed layer wind field.

The wind field is determined by objective analysis of available upper-air observations approximately 1500 m above mean sea level. Removal and transformation of the pollutant mass is treated linearly.

SO_2 emissions from the SURE program were used in ENAMAP-1 model simulations. The months of January, April, August, and October 1977 were chosen for model evaluation.

ASTRAP Model

The Argonne National Laboratory has developed the Advanced Statistical Trajectory Regional Air Pollution Model (ASTRAP) under the MAP3S Program for simulating regional sulfur concentrations and depositions on a monthly and annual basis (Shannon, 1980).

The ASTRAP model takes a statistical approach to long-term regional modeling rather than a day-by-day simulation technique. The ASTRAP model is based on the assumption that for long-period averages, i.e., one month or longer, horizontal and vertical dispersion processes can be separated.

The long term horizontal dispersion of individual puffs is represented by dispersion statistics. Vertical dispersion is simulated by numerically integrating the standard one-dimensional diffusion equation to a height of 2100 m.

The transformation and dry deposition processes are linearly parameterized. The wet deposition is a one-half power relationship of precipitation rate. In the ASTRAP Model, seasonal and daily variations in all parameters are taken into account. A wind field is developed from National Weather Service (NWS) data at 1000 metres in the winter and 1800 metres in the summer.

Preliminary model runs have been made in the eastern United States and Canada using 1974 and 1975 meteorological data. The emission inventory (MAP3S) consisted of both point and area sources emissions in the eastern United States and Canada. The model results were then compared with measurements from the SURE data network for 1977 and 1978.

RCDM Model

The Regional Climatological Dispersion Model (RCDM) of Teknekron Research, Inc., (TRI) is an application of the basic model developed by Fay and Rosenzweig (1980). Analytical solutions to the coupled diffusion equations for sulfur dioxide and sulfate concentrations are found through the use of simplifying assumptions. The horizontal eddy diffusivity and conversion and removal rates are uniform in space.

The TRI formulation of RCDM attempted to apply temporal and spatial averaging of the wind data sufficient to eliminate most of the detailed fluctuations while preserving the mean transport field that results from a large number of trajectories. The compromise utilized was to create a seasonal and annual resultant wind vector for each emission cell (state, province or subunit thereof) by averaging available upper air wind data for the eastern U.S. and southeastern Canada (Niemann, et al., 1980).

The conversion and removal parameters used in the RCDM are the same as those used by Fay and Rosenzweig from the literature with an annual mixing height of 1000 metres. The RCDM uses a simple deposition velocity technique to calculate dry and wet depositions of sulfur dioxide, sulfate and total sulfur. The RCDM has been evaluated against historical ambient data and current sulfur dioxide and ambient sulfate and wet sulfur deposition data.

Discussion of Input Parameters Used

Table 3-1 outlines the parameter values for the meteorological and chemical processes used in these models.

The sulfur dioxide transformation rate to sulfate is set at 1%/hour in most models with some seasonal variability allowed.

The sulfur dioxide dry deposition velocity for the Canadian models and ASTRAP is set near 0.5 cm/s and double that for RCDM and ENAMAP. The sulfate dry deposition velocity used varies from 0.05 cm/s (OME-LRT) to 0.4 cm/s (ASTRAP) with most models using 0.1 cm/s.

The parameterization of wet removal shows the greatest variability. Some models use percentage removal as a function of rainfall rate (with 100% removal occurring at rates ranging from 0.67 to 14 mm/h), while others use a constant removal rate during precipitation (with 100% removal occurring in 27.6 to 2.8 hours).

TABLE 3-1. REGIONAL MODEL PARAMETER VALUES FOR EASTERN NORTH AMERICA TRANSPORT SIMULATIONS

PARAMETER	RCDM	ENAMAP - 1	ASTRAP	OME	AES
SO_2 transformation rate (%/hour)	2.4×10^5 [f]	1.0	Diurnal Cycle Summer 1.1 Winter 0.55	1.0	1.0
SO_2 dry deposition velocity (cm/s)	0.83 [h] (1.7×10^5)[g]	1.0	Summer 0.4 (avg.) Winter 0.25 (avg.)	0.5	0.5
$SO_4^{=}$ dry deposition velocity (cm/s)	0.63 [h]	0.2	Summer 0.4 (avg.) Winter 0.25 (avg.)	0.05	0.1
SO_2 wet removal rate (%/hour)	(1.2×10^5)[g]	28P(t) [a]	$100(h/4)^{1/2}$; $h \leq 4$ [b]	10.8 [e]	30,000 [c]
$SO_4^{=}$ wet removal rate (%/hour)	(1.6×10^5)[g]	7P(t) [a]	100 : $h > 4$ [b]	36 [e]	850,000 [c]
Mixing depth (m)	1000	Winter 1150 Spring 1300 Summer 1450	up to 2100 (10 levels)	1000	Climatological [d] by month (mean = 1200m)
Wind Data	resultant average vector wind field, $\overline{U} = 3.2$m/s $\overline{\theta} = 265°$ True	80 x 80 km grid, representative grid square average $\overline{U} = 0.75\ U_{850mb}$ $\overline{\theta} = \theta_{850mb} - 15°$	191 x 191 km grid, $1/R^2$ analyzed to grid points	long term wind statistics $\sigma_x = U_mT$ $\sigma_y = V_mT$ $U_m = 10$ m/s $V_m = 6$ m/s	objectively analyzed at 4 levels on 381 x 381 km grid
		(1977)	(1975)		(1978)

[a] Precipitation rate, P(t) in mm/hr.

[b] Precipitation rate, h, in mm/6 hr.

[c] Scavenging ratio

[d] Based on Portelli (1977) & Holzworth (1967)

[e] Function of average length of wet and dry periods (applies during wet period only)

[f] Chemical conversion time scale (seconds)

[g] Total wet and dry depletion time scale (seconds)

[h] Dry and wet combined

The wind data varies from long-term statistical to 6-hourly, objectively analyzed fields* on grids ranging in size from 80 km x 80 km to 381 km x 381 km. Mixing depth varies from climatological arrays through actual calculated values (from upper air ascents) to fixed values between 1000-1500 metres.

Appendix 5 gives a more detailed description of each of the five selected models and a summary of some preliminary comparisons with measured data.

---

* Objective analysis routines variously use inverse-square averaging, arithmetic averaging within a grid square, and a 3-dimensional data assimilation scheme that incorporates hydrostatic and height-wind balance routines.

Chapter 4

SOURCE REGION AND SENSITIVE AREA DEVELOPMENT AND TRANSFER MATRIX OPERATION

The application of LRT models to the development of quantitative relationships between pollution source areas and sensitive receptor areas in the form of transfer matrices requires the identification of appropriate geographical groupings of sources and the identification of sensitive receptor areas.

The transfer matrix application is immediately amenable to control strategy development in that manipulation of source contributions to sensitive areas is easily carried out. Because control strategies (i.e., emission limitations or reductions) would most likely be implemented on a state or sub-state basis in the U.S., and on a province or sub-province basis in Canada, a thoughtful geographical aggregation of sources or grid elements on such a basis is required for model calculations.

This need was recognized early in the EPA/DOE Acid Rain Mitigation Study (ARMS) when areas from the 80 km x 80 km SURE emission grid were aggregated into 60 larger areas which approximated state and provincial areas or represented selected areas thought to be sensitive to acid deposition. These 60 areas were constructed to reproduce total state

SO_2 emissions and boundaries as closely as possible. A table that compares the state and grid-aggregate SO_2 emission totals along with percentage differences is presented in Appendix 6. In most cases differences were less than + 15% and the largest was 32%.

For the present application the SURE grid has been expanded (from 30 x 36 to 40 x 42 elements) to the north and east to include more of southeastern Canada. The expanded grid is now includes 63 aggregated SURE areas (see Figure 4.1), ten of which have been selected to represent major sensitive areas. The total SO_2 emissions in the SURE inventory for the eastern U. S. are thought by EPA to be too high and this situation is presently being reviewed by comparing the SURE SO_2 emissions for the utility sector with those computed using the EPA AIR-TEST program. As a result of this review, revisions in the U.S. emissions inventory are likely to occur during Phase II.

In Phase I and planned Phase II activities, U.S. and Canadian modeling efforts have used different grid systems and areas to generate source-receptor (transfer) matrices. Canadian efforts, similarly based upon the aggregation of sources, have resulted in the delineation of 11 regions. Because of this difference, the 11 Canadian regions, which are based on an aggregation of sources on a 127 km x127 km polar stereographic grid, were projected onto the 63 U.S.

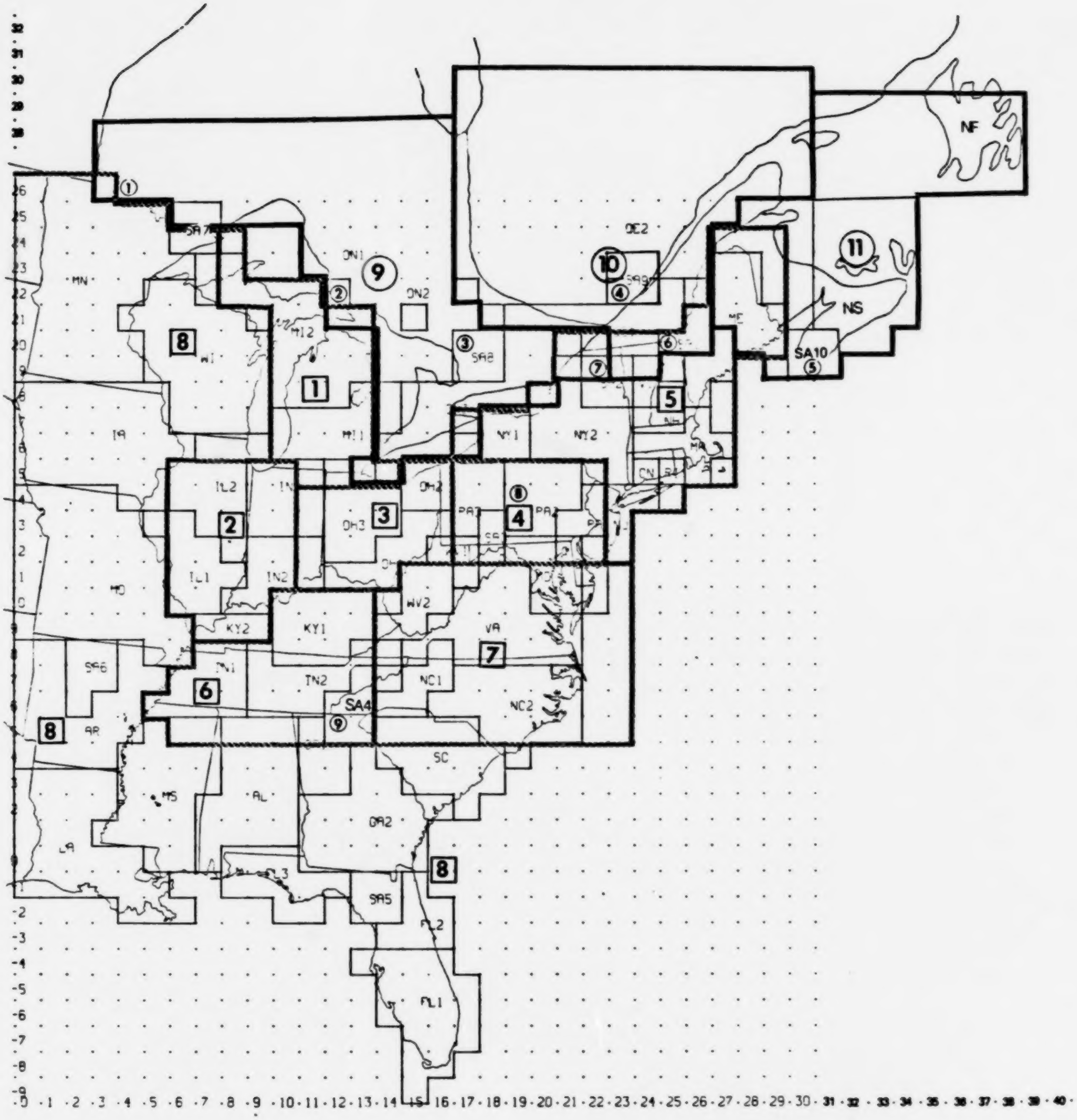

NF
QE2
⑩
SA9
④
⑪
NS
SA10
⑤
ME
ON1
⑨
ON2
②
③
SA8
①
SA7
MN
8
WI
MI2
1
MI1
IA
⑥
⑦
5
NH
MA
NY1
NY2
CN
IL2
IN
2
IL1
IN2
OH2
OH3
3
PA1
⑧
4
PA2
MO
KY2
KY1
WV2
VA
7
SA6
TN1
6
TN2
NC1
NC2
SA4
⑨
8
AR
SC
MS
AL
GA2
LA
FL3
8
SA5
FL2
FL1

Figure 4.1: Map of eastern North America showing the two sets of geographical regions used in Work Group 2 modeling. Light and heavy (solid in Canada; slashed in U.S.) lines outline regions used by U.S. and Canadian models, respectively. U.S. aggregate SURE grid regions are identified by 2 or 3 character alpha-numeric labels (light), with sensitive areas having 'SA' as the first two characters. Canadian-model source regions are identified by large numbers, in boxes in the U.S. and in circles in Canada, and sensitive areas are identified by small numbers in circles. (See Appendix 6.)

areas, which are based on the 80 km x 80 km Transverse Mercator grid. This projection was necessarily done in an approximate way and some mechanical difficulties and uncertainties still exist in relating the 11 Canadian regions to the 63 U.S. areas.

SO_2 emissions in the 11 Canadian regions and in the 63 U.S. areas are given for comparative purposes in Appendix 6. In addition, a comparison was made between SO_2 emissions used in the Ontario Ministry of the Environment (OME) and the Atmospheric Environment Service (AES) models. Basically, the OME model used emissions that were about 80% of the total emissions used in the AES model for the 8 regions in the U.S., while the emissions used for the 3 regions in Canada were approximately equivalent.

It is expected that early in Phase II, Work Group 2 will be provided with an "agreed" and "unified" Canada/U.S. emissions data base which will be made available to all participating modeling groups. Such a common inventory could be expected to lead to improved agreement in model results.

The Work Group will develop a common basis for specification of source and sensitive areas during Phase II for use in the development of refined transfer matrices for application in Phase III and beyond. This effort will be coordinated with other Work Groups as appropriate for their particular areas of responsibility.

The specification of sensitive areas is primarily the responsibility of Work Group 1, in coordination with Work Group 2. However, in order to commence modeling work, Work Group 2 chose sensitive areas that had been previously identified in the work of ARMS and of the RCG.

The Canadian sensitive receptor areas, which are actually specified as points by latitude and longitude coordinates, and the ARMS sensitive areas are listed in Appendix 6. Six of the 9 Canadian receptor areas fall within the 10 ARMS sensitive areas; two of the Canadian receptor areas are close to ARMS sensitive areas; and two of the ARMS sensitive areas are not included in the Canadian list (Arkansas and Florida). The ARMS sensitive areas were purposely selected to include at least several SURE grid squares (usually 4) and to include areas in which adverse ecological impacts from acid deposition had been detected or were considered probable. (The principal reason for selection of each of the 10 ARMS sensitive areas is provided in Appendix 6).

For future work during Phases II and III Work Group 2 expects that Work Group 1 will provide a list of candidate sensitive areas together with their sensitivities and target sulfur deposition objectives. It is expected that many of these sensitive areas will coincide with those already selected for initial analysis.

The development of quantitative relationships between the sources and receptors identified above is an application for which LRT models are uniquely suited. Specifically, this entails computing how much pollution, in terms of concentration or deposition, arrives at a specified receptor area from a variety of source regions. This information can be presented in matrix form for all parameters of interest, as absolute values, percentages, or normalized values.

Mathematically, the transfer matrix concept may be expressed as

$$D_j = f_{ij} Q_i$$

where D_j is the deposition (or concentration) of the parameter of interest at receptor 'j'; Q_i is the strength of source 'i'; and f_{ij} is an element of the transfer matrix which describes the relationship between the two. The LRT models are used to determine the transfer matrix, examples of which are presented in Chapter 5.

An important future application would involve the estimation of the reduction in D_j (concentration or deposition) due to a reduction in emissions Q_i. Examples of the manipulations which can be undertaken with the relationship include:

(1) The maximization of the reduction in deposition with given constraints on emission reductions.

(2) The minimization of the cost of emission reduction given constraints on the deposition reduction.

These applications are described in more detail in Appendix 7.

Because of the large amount of data to be handled in transfer matrix operations and due to the complexity of the operations themselves, an integrated transfer matrix processing system is under development. This system will be accessed by Work Groups 3A and 3B during Phase II and beyond in order to provide the rapid-response analyses required to support the negotiations following Phase II. The integrated matrix processing system has been designed to handle a variety of inputs and to provide the specific outputs needed by Work Groups 2, 3A, and 3B. At present the integrated processing system consists of five computer programs which format, intercompare, plot, and manipulate the matrices. It is expected that the integrated matrix processing system will be refined and that the operations in program five (least-cost, source-receptor optimization) will be specified by Work Group 3B in Phase II. This system is described in more detail in Appendix 7.

Chapter 5

SOURCE-RECEPTOR RELATIONSHIPS

Introduction

Several long-range transport models are currently available for predicting sulfur deposition and for developing source-repector relationships; these were described in Chapter 3. No models are currently available for predicting either acidity or nitrate deposition.

Eastern North America can be divided up in a variety of ways for purposes of source-receptor modeling as described in Chapter 4. In the United States many modelers have used a basic 80 km grid with the cells aggregated into 63 geographical areas. The ASTRAP and ENAMAP models have been run using the original ARMS 60 areas to produce a 60 by 60 transfer matrix. Of particular interest in the present context is the impact of individual or combined source areas on the ten areas designated as sensitive receptor areas. At a later date when other potential effects (e.g. on agriculture or buildings) are being considered, different sets of receptor areas may be considered.

The Canadian approach has been to aggregate into 11 large source regions, 8 U.S. and 3 Canadian, and 9 receptor areas. Most of the receptor areas selected are the same as those used by the U.S.

The source-receptor relationships

a) United States Models

The results of running the three U.S. models are contained in separate computer print-out files on a 60 by 60 matrix. The matrices are to be consolidated into the eleven source areas used for the Canadian models. These matrices also can be reduced in size by selecting out the columns representing the sensitive receptor areas from the set of all 60 areas. The values are to be presented in the same three ways discussed below for the Canadian models.

For the purpose of illustrating their use, a selected portion of one of the U.S. 60 x 60 matrices is shown in Table 5.1. The three largest U.S. emission source regions (Southern Ohio, Southern Michigan and Southern Indiana) and the largest Canadian emission source region (Sudbury) were chosen, and 10 of the 60 regions were selected as receptors because of their known sensitivity to acid deposition.

This resulted in the 4x10 matrix shown in Table 5.1, and its use can be illustrated as follows. If one is interested in the impact of a given source, for example S Ohio, one reads down the column headed "46 S. Ohio" and the annual deposition of sulfur at each receptor is given. Conversely, if one is interested in the contribution to a given receptor area, for example Adirondack, one reads across the row headed "8 Adirondack".

Table 5.1 Total Annual Sulfur Deposition as Computed from the ASTRAP Model (KgSha^{-1} yr^{-1})

	Selected Major Source Areas			
	45 S. Ind.	46 S. Ohio	49 S. Mich.	55 Sudbury
Sensitive Receptor Areas	AST[b]	AST	AST	AST
2. New Hampshire	0.63	1.3	1.6	1.0
8. Adirondack	0.91	2.0	2.5	1.3
15. Pennsylvania	2.3	9.0	2.8	0.15
25. S. Appalachia	2.2	2.2	0.17	0.01
33. Florida	0.08	0.06	0.01	0.0
39. Arkansas	0.38	0.15	0.06	0.0
53. Boundary Waters	0.11	0.11	0.20	0.01
56. Ontario	1.1	2.0	5.1	6.4
58. Quebec	0.61	1.1	2.2	3.5
1. S.N.S.[a]	0.43	0.88	1.1	0.83

[a] Sulfur deposition in Southern Nova Scotia sensitive area assumed same as for Maine.

[b] Annual average: computed from winter and summer months.

b) Canadian models

The results from the Canadian models are presented in Appendix 8 in 11 x 9 transfer matrices; for each model annual values of each of the following five variables are given:

(1) ambient SO_2 concentrations
(2) ambient SO_4 concentrations
(3) dry deposition of sulfur
(4) wet deposition of sulfur
(5) total deposition of sulfur

In each case information on the variable is presented in three ways:

(1) normalized to a unit emission from each source
(2) as a percentage contribution from each source
(3) as an absolute value

This gives a total of 15 tables so that there is maximum flexibility in how the results can be used. To provide an example, and to illustrate the use of source-receptor matrices for the Canadian models, Table A8-10 from Appendix 8 is reproduced below as Table 5-2. While the sensitive receptor areas match fairly closely those used by the U.S. modelers, the source regions differ and are much larger. Thus, a direct comparison cannot be made between the results presented in Tables 5-1 and 5-2.

Table 5-2 is used in exactly the same way as Table 5-1. For example, if one is interested in the impact of a given source region such as Ohio, one reads across the row headed "3. Ohio".

Table 5.2: Example of transfer matrix from Appendix 8. Total annual sulfur deposition in kg ha^{-1} yr^{-1}
(Table A8-10)

Source Regions	Models	Receptor Areas								
		B.Waters (1)	Alg. (2)	Musk. (3)	Que. (4)	S. N.Sc. (5)	Vt. NH. (6)	Adir. (7)	Penn. (8)	Smokies (9)
1 Mich.	MOE	0.10	0.75	1.8	0.58	0.66	1.0	1.6	3.4	0.19
	AES	0.30	4.5	6.7	1.7	0.60	1.6	2.2	4.7	0.30
2 Ill. Ind.	MOE	0.28	1.3	1.8	0.78	0.93	1.2	1.7	4.5	2.8
	AES	0.30	3.5	3.4	0.80	0.40	0.90	1.4	4.2	4.3
3 Ohio	MOE	0.16	0.65	1.4	0.77	1.2	1.4	2.2	10.2	1.0
	AES	0	0.90	6.7	1.8	1.2	3.9	5.9	28.9	2.2
4 Penn.	MOE	0.06	0.26	0.65	0.46	0.91	0.90	1.4	11.8	0.24
	AES	0	0.40	1.9	1.2	0.70	2.8	4.3	26.0	0.20
5 N.York to Maine	MOE	0.05	0.18	0.52	0.66	2.8	1.6	2.3	0.93	0.11
	AES	0	0.40	1.2	2.5	6.5	4.7	6.1	1.1	0
6 Kent. Tenn.	MOE	0.07	0.23	0.35	0.21	0.31	0.33	0.44	1.3	5.0
	AES	0	0.30	1.3	0.10	0.20	0.40	0.90	3.6	15.2
7 W.Virg. to N.C.	MOE	0.08	0.27	0.57	0.46	1.0	0.83	1.1	3.7	0.62
	AES	0	0.10	0.50	0.60	0.50	1.5	2.0	7.3	1.5
8 Rest of (USA) Fld to Mo. to Minn.	MOE	0.22	1.1	0.94	0.37	0.36	0.51	0.68	1.1	2.9
	AES	2.5	4.2	1.8	0.40	0.30	0.50	0.90	3.4	18.7
9 Ontario	MOE	0.14	1.2	3.7	2.3	1.2	2.4	2.6	1.2	0.09
	AES	0.10	3.9	13.2	3.1	1.3	3.8	5.4	3.1	0.10
10 Quebec	MOE	0.06	0.25	0.46	2.3	1.0	3.6	0.86	0.17	0.03
	AES	0.10	0.50	1.2	4.3	1.5	7.2	2.5	0.20	0
11 Atlantic Provinces	MOE	0	0.01	0.02	0.07	0.35	0.07	0.04	0.02	0
	AES	0	0	0	0.10	3.2	0.10	0	0	0
Western Canada	AES	0.60	0.20	0.20	0	0	0	0.20	0	0
Total Concentration	MOE*	1.2	6.2	12.2	8.9	10.8	13.8	14.9	38.3	13.0
	AES	3.9	18.8	38.1	16.7	16.3	27.4	31.8	82.5	42.6

*Note: In order to calculate the total deposition at each site, the deposition resulting from background in the amount of 0.2 g.m-2.yr-1 (or 2.0 kg.ha-1.yr-1) should be added to this row.

Conversely, the contributions at a given receptor such as Muskoka can be seen by reading down the column headed "Muskoka".

A comparison of the predictions of the two Canadian models shows that, whilst they agree reasonably well with each other, the AES model generally predicts larger values than the OME model for the absolute values and the emission-normalized values in Tables A8-1 through A8-10.

Comparison of matrix outputs with each other and observations

Each of the models discussed in this Chapter has been compared with observations as described in Appendix 5. But, since the observations consist only of the deposition or ambient concentration at a monitoring station due to all sources, there is no way that each of the contributions in the matrices can be directly verified. However, the total contribution of all sources at each receptor predicted by the models can be compared with the observations. If these do not agree, then clearly there is no justification for using the models further. If the predicted and observed depositions do agree reasonably well, then in the absence of any evidence to the contrary, it can be assumed that the individual contributions in the matrices will probably also be realistic.

Table 5.3 - Comparison of the predicted annual wet deposition of sulfur (kgSha^{-1}yr^{-1}) from selected LRT models compared to the measured values

	Sensitive Areas	Model predictions*				Observed Values**
		Canadian		United States†		
		MOE	AES	ASTRAP	RCDM	
1	Boundary Waters	2.6	1.5	$< 5^+$	5	6
2	Algoma	4.7	10.4	10	17	10
3	Muskoka	7.1	17.6	22	20	18
4	Quebec - Montmorency	5.9	9.0	15	13	20
5	Southern Nova Scotia	6.8	5.9	5	6	12
6	New Hampshire	7.9	13.1	15	13	9
7	Adirondack - Whiteface	8.3	15.7	19	18	12
8	Pennsylvania - Penn State	17.2	33.5	>25	26	19
9	Southern Appalachians	7.4	16.7	9	18	12
10	Florida			< 5	8	9
11	Arkansas			< 5	10	9

* Modeled values include wet deposition of SO_2 and SO_4 expressed as S.

** See Table 6.1

+ Uncertainty due to limited number of isopleths of model predictions.

† Final ENAMAP and ASTRAP results were not available when the report was finalized.

In Table 5.3, the variations among the model predictions are immediately obvious and are due to many diffences such as: the variations in emission inputs; the differing meteorology in the years chosen to run the models; the differences in the values chosen for SO_2 to SO_4 conversion rates and wet and dry deposition. Resolution of these differences will be the subject of a detailed model intercomparison by Work Group 2 as part of Phase II.

The most detailed and reliable deposition observations are for the wet component. The results presented in Chapter 6 for the estimated wet deposition rate at the sensitive sites are compared in Table 5.3 with the predictions of the models obtained from Appendix 8, Table A8-9, and from the U.S. model outputs.

For many of the sensitive areas, the predictions of the two Canadian models agree with the observations reasonably well, with the AES model tending to overpredict and the MOE model tending to underpredict.

We recognize the importance of advising the reader about the confidence with which one can make use of the transfer matrices in this chapter and Appendix 8. These matrices have not yet been thoroughly verified or intercompared, so that it is difficult to assign a quantitative measure of uncertainty to the matrix elements. The differences among model estimates for individual matrix elements are perhaps the best indication of the uncertainty in these values at the present time. On the whole, the matrix elements representing transport between major source areas and those receptor areas within reasonable transport range of the source areas are in relatively good agreement across the models. Where obvious differences exist, efforts have been initiated to determine the cause for disagreement. These efforts are expected to help us understand the reasons for most of the major differences before the end of Phase II.

In the meantime all the model results must be regarded as preliminary. The results are presented here primarly to indicate the type of information and the format that can be provided for use by others. The results also give some useful indications, or trends, regarding the relative importance of various source regions on the sensitive receptor areas presently of interest. But at this time the absolute values of the numbers in the matrices should not be given too much importance and certainly the results of any one model should not be taken in preference to the others. It is expected that Work Group 2 in Phase II and beyond will provide "best estimates" of the values in matrices based on the results of all models, and that other Work Groups will still be advised not to use results of individual models as definitive.

Chapter 6

MONITORING

Whether needed for the study of atmospheric transport or ecological and other effects, the measurement of atmospheric pollutants and precipitation composition and deposition is a vital aspect of understanding long-range transport and acid rain. Modeling research and applications require ground truth measurements with which calculations can be compared. Ecological and other impact studies require the amount of atmospheric input to relate quantitatively loadings to effects. A multistage monitoring program is a necessity to understand both the transport and chemistry in air and their trends as well as the ecological consequences of atmospheric deposition.

In addition, during future Phases, two potential applications of monitoring networks will require evaluation. These are the possible use of monitoring networks to assess the efficacy of control strategies, and the possible use of meteorological and air quality networks as a supplemental part of control strategies.

Monitoring, at least of the chemistry of precipitation, has not been consistently maintained in North America. European scientists began a large international network in the mid-1950's which has been continued more or less intact to the present. Only in recent years have limited commitments been made to long-term monitoring in Canada and the United States.

Precipitation chemistry monitoring networks in Canada and the United States are of three types: global background, national trends and research support. The small number of global background sites are located in remote areas where there is little or no local or even regional pollution. Such sites include American Samoa, Barrow, Alaska, and others. These stations identify long-term trends in the global spread of pollution.

Currently the national trends networks measure the composition of precipitation and wet deposition using wet-only collectors for both atmospheric and ecological purposes. They are long-term, country-wide, national networks: the Canadian Network for Sampling Precipitation (CANSAP), and the National Atmospheric Deposition Program (NADP), a cooperative program involving several U.S. agencies. Several other networks with similar objectives, including those of the Tennessee Valley Authority, EPA Region V, the Ontario Ministry of the Environment and the Great Lakes Precipitation Chemistry Network, are more regionally oriented.

Other networks, such as those of the Electric Power Research Institute (ERPI), of the Multi-State Atmospheric Power Production Pollution Study (MAP3S), Ontario Hydro and the Air and Precipitation Monitoring Network (APN), fall into the third category - research support networks. They are designed primarily to support studies in atmospheric transport, chemistry, and modeling.

As a result of the increased activity in monitoring during the last five years, a combined set of data for North America is now emerging from the Canadian and U.S. networks. Combining several network data sets from 1976 to 1979, Figure 6.1 shows a map of hydrogen ion (H^+) deposition over the North American continent (Wisniewski and Keitz, 1980). The 50 and 10 mg m^{-2} lines represent approximately 4.3 and 5.0 pH lines, respectively. The map shows large acidic deposition in the northeastern part of the United States and southeastern part of Canada. It has been postulated that the geographic extent of increasing rain acidity is spreading toward the southeast and midwest with all states east of the Mississippi River now receiving some degree of rain acidity. Some west-coast sites in both countries also show relatively large hydrogen ion deposition based on recent measurements.

Since it will be some time before models will be able to calculate hydrogen ion deposition, the sulfur deposition values in precipitation may be the best data for comparison with model results. A map of the wet deposition values of sulfur for 1977 in eastern North America is given in Figure 6.2. (Galloway and Whelpdale, 1980). The problem of comparing model results with such data is obvious in view of the complexity of the deposition field. Deposition fields of other substances (e.g., nitrate and ammonium ion) are also necessary for a more complete description of the acid deposition phenomenon. In

Figure 6.1 : Mean annual hydrogen ion (H^+) deposition in precipitation for period 1976-1979 (mg m^{-2} y^{-1}). Deposition values are derived from mean pH and mean annual precipitation. Adapted from Wisniewski and Keitz (1980).

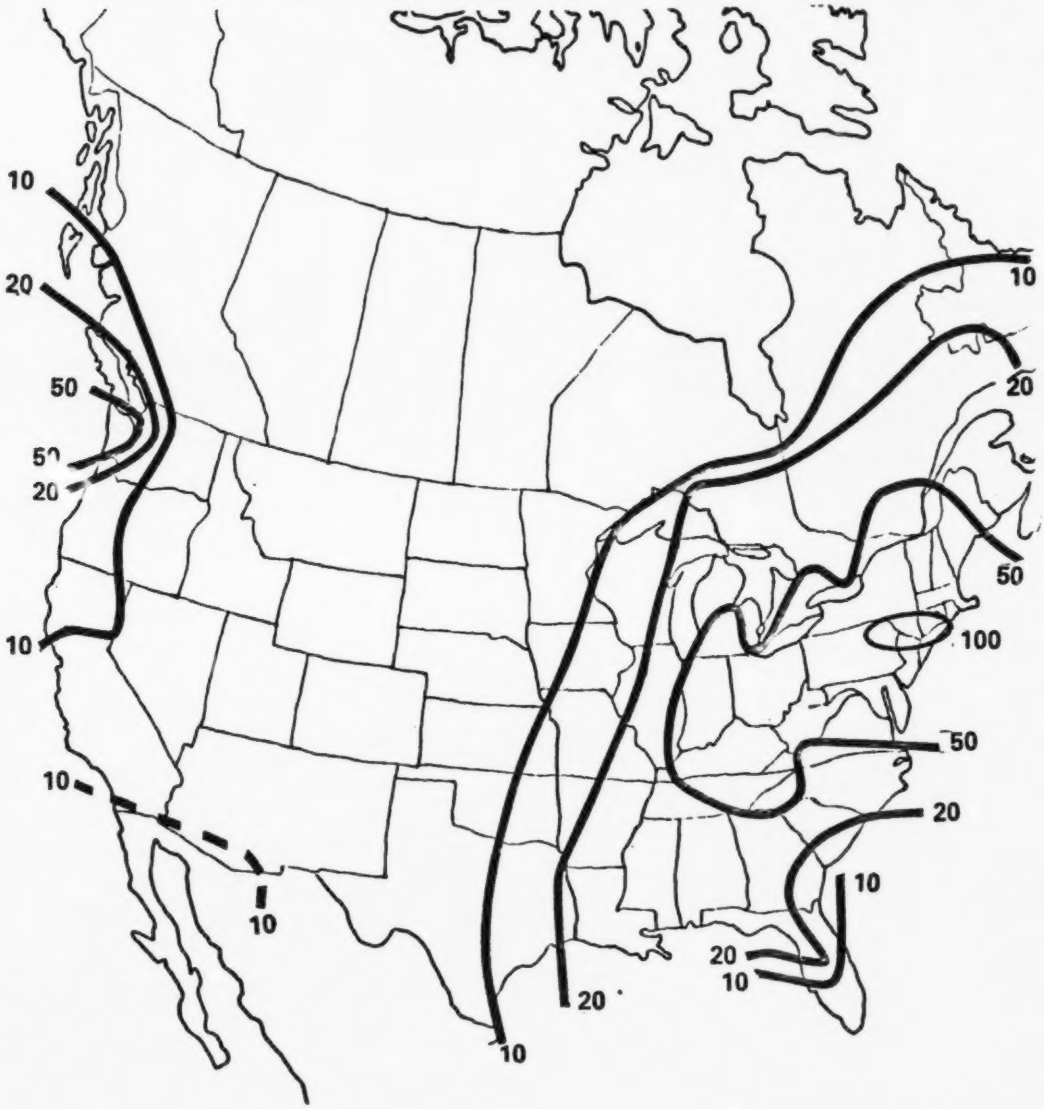
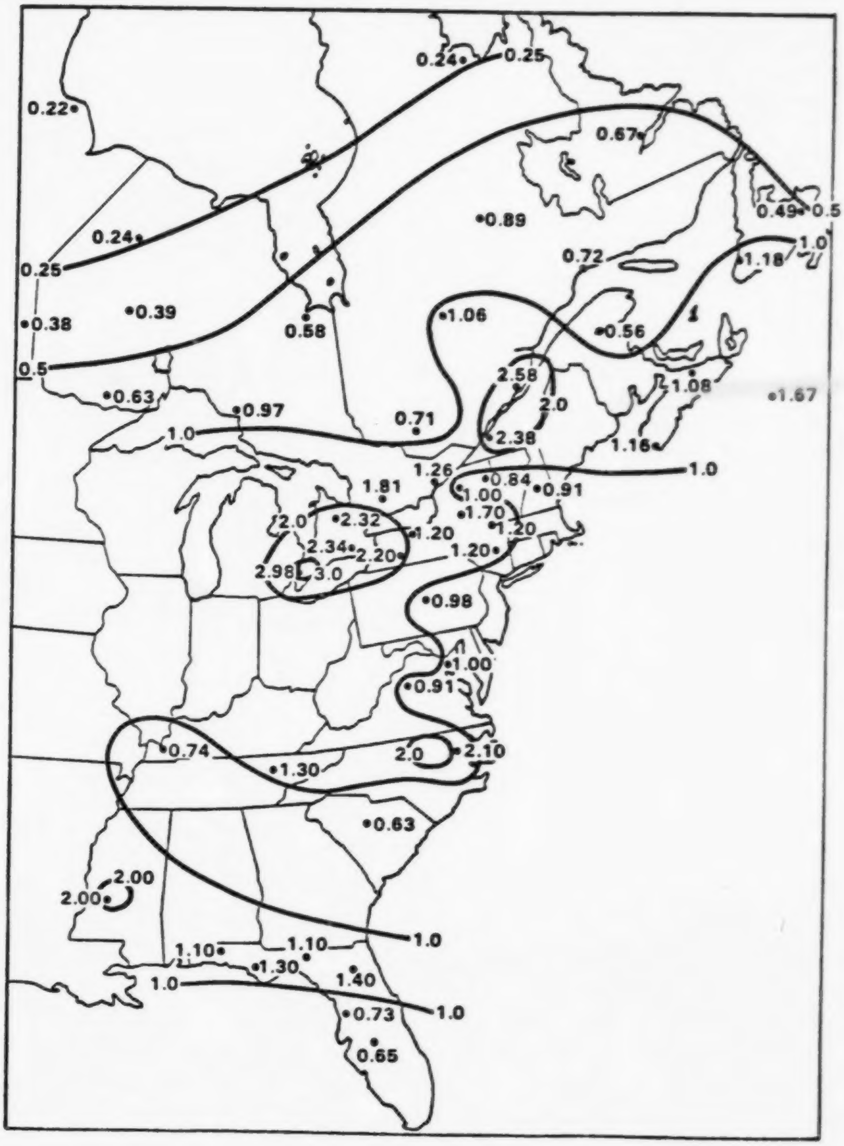

10
20
50
50
20
10
10
10
10
20
50
100
50
20
10
20
10
20
10

Figure 6.2 : Wet deposition of sulfate (SO_4) in precipitation in eastern North America for 1977 (g S m^{-2} y^{-1}). Adapted from Galloway and Whelpdale (1980).


0.24
0.25
0.22
0.67
0.49
0.5
0.89
0.24
0.25
0.72
1.0
1.18
0.38
0.39
0.58
1.06
0.56
0.5
2.58
1.08
1.67
0.63
0.97
0.71
2.0
2.38
1.0
1.16
1.0
1.26
0.84
1.81
1.00
0.91
2.0
2.32
1.70
1.20
1.20
2.34
2.20
1.20
2.98
3.0
0.98
1.00
0.91
0.74
1.30
2.0
2.10
0.63
2.00
2.00
1.0
1.10
1.10
1.30
1.40
1.0
1.0
0.73
0.65

any given year deposition patterns could be quite different from a long-term average due to variations in meteorological parameters, such as the wind and precipitation fields.

Besides the natural variability of precipitation chemistry, the methods used to collect, transport, store, and analyze samples contribute to possible errors in the final data. The isopleths shown in Figures 6.1 and 6.2 were based on data from networks with different measurement techniques. Also, the level of quality assurance varied from network to network. With these considerations in mind, a rough estimate of error for individual data points used in the figures and for values in Table 6.1 can be made of hydrogen deposition to be as high as +50% and of sulfur deposition to be as high as ±25%. As better quality assurance techniques are applied and a large statistical base established, error estimates can be refined.

One of the goals of this Canada - U.S. study is the quantitative evaluation of transport of material through the atmosphere and deposition on sensitive areas. The amount of wet deposition to sensitive areas can be estimated from recent monitoring data collected since 1977. Some such estimates of annual wet deposition of hydrogen and sulfate ion to specified sensitive areas are given in Table 6.1. As a more extensive record of measurements is compiled, both our confidence in average annual deposition values and our awareness of possible deviations of individual yearly values will increase.

Table 6.1 Estimated annual wet deposition of hydrogen and sulfate ion to specified sensitive areas. These data must be considered preliminary. Errors in H^+ and SO_4 values are estimated to be as high as ±50% and ±25%, respectively.

Sensitive Area*	Annual Wet Deposition H^+ (mg H $m^{-2}y^{-1}$)	 SO_4 (g S $m^{-2}y^{-1}$)**
Boundary Waters	10	0.6
Algoma	30	1
Muskoka	70	1.8
Quebec - Montmorency	40	2.0
Southern Nova Scotia	30	1.2
New Hampshire	50	0.9
Adirondack - Whiteface	50	1.2
Pennsylvania - Penn State U.	90	1.9
Southern Appalachians	60	1.2
Florida	30	0.9
Arkansas	30	0.9

* See Figure 4.1 and Appendix 6 for sensitive area locations.

** To convert sulfate loading expressed in terms of S (as shown in table) to loading in terms of SO_4, multiply by 3.

Seasonal and monthly deposition values may vary widely because the amounts deposited depend not only on the varying composition of the rain but also on the highly variable amount of rain that falls.

The measurement of the dry deposition component is at present not possible because there exists no generally accepted method for routine monitoring of dry deposited material.

Chapter 7

CONCLUSIONS, RECOMMENDATIONS, AND PHASE II WORK

Conclusions

Work Group 2 has reviewed the modeling, monitoring and research aspects of the atmospheric behavior of acid-forming pollutants, particularly sulfur, between their source regions and deposition areas. The role, capabilities and applications of selected transport models from both Canada and the U.S. have been described. As a part of the Phase I work, "first cut" transfer matrices to describe source-receptor relationships have been constructed by the Group. Comparisons of model results were made with deposition data collected by networks in both countries.

The following are the major conclusions of the Group

(1) The source-receptor matrices obtained to date are of an interim nature, and must be viewed as only a first attempt to quantify relationships. Revisions and refinements will be made in the transfer matrices during future Phases.

(2) Monitoring data of high quality are crucial for the evaluation of models, and, at present, significant uncertainties exist in these data. The continuation of existing monitoring networks, and of strong quality assurance programs are essential to ensure that valid monitoring data will be available for future in-depth comparisons with model calculations.

(3) The above uncertainties notwithstanding, the results from the models and the monitoring networks which have been presented can serve for the initial development of pollution control stratagies.

(4) A strong research and development effort is essential for the continuing upgrading of routine modeling and monitoring activities, and for the further development of a sound base of scientific knowldge for the agreement.

Recommendations

The first set of recommendations pertains to matters requiring consultation or clarification among the various Work Groups. Work Group 2 recommends that:

- there be continuing consultation with Work Group 2 regarding the uses, results, and significance of the Phase I transfer matrices;
- a common glossary of terms be developed to insure uniformity of technical language in all Groups (see Appendix 3 to this report);
- common units of measurement be used, preferably the SI (International System) units;
- field, analysis, and interpretive activities of Work Groups 1 and 2 be coordinated, as far as possible, in order to gain maximum benefit from the efforts invested.

The second set of recommendations is directed to clarifying aspects of Phase II (and beyond) work. We recommend that:

- the relative importance of hydrogen and sulfate ion deposition, as a measure of damage, be examined and resolved, as far as possible at this time;
- key atmospheric parameters, from an effects point of view, be identified;
- the urgency/importance of investigating nitrogen oxide deposition be discussed and resolved, as far as possible at this time;
- the need for investigating the various time scales of adverse effects from acid deposition, and associated Work Group 1 priorities, be established;
- the priority of considering the long-range transport of other materials (e.g., metals, synthetic organics, particulates) be established;
- the need to model past emissions and deposition of sulfur and other species be reviewed, in view of the paucity and uncertainty of past data, and the likelihood of a poor return for our efforts;
- the number and type of emission scenarios to be run in future Phases be clarified;
- the name of Work Group 2 be changed to "Atmospheric Sciences and Analysis Work Group" to reflect more accurately our charge;

- the following be added to our terms of reference: " - evaluate and employ available field measurements, monitoring data and other information;";
- a critical path analysis of tasks and information needs be completed by the Coordinating Committee or Work Group 3A and distributed to ensure a coordinated effort;

The third set of recommendations are more general in nature and concern the broader aspects of the acid deposition problem. We recommend that:

- a long-term commitment be made by governments to the operation of national and regional precipitation chemistry networks, specifically CANSAP and NADP, with increased effort and resources being allocated to quality assurance/control and data analysis/ interpretation aspects;
- efforts be made to develop more comprehensive deposition information, including that on nitrate and ammonium ion, alkaline constituents, and dry deposition;
- communications within and coordination of scientific programs in the two countries continue and be enhanced. (The structure for this exists: MOI Work Groups provide the near-term reporting function; the RCG is structured to provide a longer-term coordination function; and the NAS-RSC panel can be expected to provide the important review function.)

Phase II Work

The work plan of Work Group 2, prepared during Phase I, outlined the major tasks of the Group and their timing. Figure 7.1 shows, as a bar graph, a slightly revised set of tasks and timing for Phase II and beyond.

In order to proceed in Phase II with a number of its tasks, Work Group 2 requires, in addition to those items identified as recommendations, several specific inputs from other Work Groups. These are needed before further revision of the transfer matrices is undertaken. They are

- a current, agreed, 'unified' sulfur emissions inventory for North America, on an annual and seasonal basis by February 1, 1981 (from WG 3B);
- agreement on the number and delineation of source regions in the two countries for use in transfer matrix calculations (input from WG's 3A and 3B);
- agreement on sensitive receptor areas in both countries (from WG 1).

TABLE 7.1

WORK GROUP 2 ACTIVITY SCHEDULE (REVISED 80/12/19)

	ACTIVITY	Nov 15	Jan 15	Mar 30	May 15	Oct 81	Jan 82
1	Receive unified U.S./Canada present S inventory (annual) from 3B	--------	----?				
2	Receive unified U.S./Canada present S inventory (seasonal) from 3B	--------	----?				
3	Receive past/future S inventories (annual and seasonal) from Group 3B	--------	----?				
4	Receive unified U.S./Canada N and HC inventories from Group 3B	--------	----?				
5	Final choice of source and receptor areas from Group I, 3A, and 3B	--------	----?				
6	Settle meteorological period for verification	complete					
7	Settle meteorological period for general use	--------	--------	---x			
8	Choose selected models	complete					
9	Review and document model parameters	complete					
10	Demonstrate model output	complete					
11	Demonstrate model use	complete					
12	Evaluate and intercompare selected models	--------	--------	------	------	----x	
13	Glossary	complete					
14	Assess and use measured data	--------	---x---	------	----x-	------	-------x
15	Develop and demonstrate transfer matrix	--------	----x--	------	----x		
16	Run reference scenarios	--------	--------	------	----x-	------	-------x
17	Review of selected atmospheric science topics	--------	--------	------	----x		
18	Formulate proposals for agreement	--------	----x--	------	----x-	------	-------x
	Timing of Phases	Phase I		Phase II		Phase III	

Comments on the status of each of the tasks listed in Figure 7.1 is given below.

Tasks 1-5: Inputs required from other Work Groups

Task 6: The year 1978 was chosen. See Appendix 9.

Task 7: To be completed early in Phase II.

Task 8: Completed. See Chapter 3.

Task 9: Completed. See Appendix 5.

Task 10: Completed. See Chapter 5 and Appendices 5 and 8.

Task 11: Completed. See Chapter 5 and Appendices 5 and 8.

Task 12: A major Phase II activity. This will be the subject of a series of workshops. See Appendix 9 for a report of the first workshop.

Task 13: Completed, but can be ammended. See Appendix 3.

Task 14: Completed for Phase I. See Chapter 6. This is a continuing activity throughout all phases.

Task 15: Completed as an interim step. See Chapter 5 and Appendix 8. Refinements will occur during Phase II.

Task 16: To be done in Phases II and III as determined in consultation with Work Groups 3A and 3B.

Task 17: Initial reviews to be done during Phase II for four topics: (i) the parameterization of chemical processes in LRT models; (ii) historical trends in precipitation composition and deposition data; (iii) wintertime deposition and chemical processes; and (iv) global and western North America rain pH.

Task 18: Ongoing.

REFERENCES

BASS, A., 1980: Modeling long-range transport and diffusion. Preprint, Procedings of the Second Joint AMS/APCA Conference on Applications of Air Pollution Meteorology, March 24-27, 1980, New Orleans, LA.

BHUMRALKAR, C.M.., W.B. JOHNSON, R.L. MANCUSCO, R.H. THUILLIER, and D.E. WOLF, 1980: Interregional exchanges of airborne sulfur pollution and deposition in Eastern North America, Procedings of the Second Joint AMS/APCA Conference on Applications of Air Pollution Meteorology March 24-27, New Orleans, LA.

CHOQUETTE, P.J. and VENA, F., 1980: Canadian SO_2 Emissions Information Package. Environment Canada.

ELIASSEN, A., 1980. A Review of Long-range Transport Modeling. J. Applied Meteorology, vol. 19, 231-240.

FAY, J.A. and ROSENZWEIG, J.J., 1980: An Analytical Diffusion Model for Long Distance Transport of Air Pollutants. Atmospheric Environment, vol. 14, 355-365.

GALLOWAY, J.N. and WHELPDALE, D.M., 1980: An atmospheric sulfur budget for Eastern North America. Atmospheric Environment, vol. 14, 409-417.

HOLZWORTH, A.C., 1967: Mixing depths, wind speeds and air pollution potential for selected locations in the United States. J. Appl. Met., vol. 6, 1039-1044.

NIEMANN, B.L., A.A. HIRATA, B.R. HALL, M.T. MILLS, P.M. MAYERHOFER and L.F. SMITH, 1980: Initial Evaluation of regional transport and subregional dispersion models for sulfur dioxide and fine particulates, Procedings of the Second Joint AMS/APCA Conference on Applications of Air Pollution Meteorology, March 24-27, New Orleans, LA.

OLSON, M.P., VOLDNER, E.C., OIKAWA, K.K. and MACAFEE, A.W., (1979): A Concentration/Deposition Model Applied to the Canadian Long Range Transport of Air Pollutants Project: A Technical Description, LRTAP-79-5, Atmospheric Environment Service.

PORTELI, R.V., 1977: Mixing Heights, Wind Speeds and Ventilation Coefficients for Canada. Atmospheric Environment Service, Downsview, Ontario, Canada. Climatological Studies No. 31, 87 pages.

SHANNON, J., 1980: Examination of surface removal and horizontal transport of atmospheric sulfur on a regional side, Procedings of the Second Joint AMS/APCA Conference on Applications of Air Pollution Meteorology, March 24-27, New Orleans, LA.

VENKATRAM, A., B.E. LEY, and S.Y. WONG, 1980: A statistical model to estimate long-term concentrations of pollutants associated with long range transport, to appear in Atmospheric Environment.

VOLDNER, E.C., M.P. OLSON, K. OIKAWA, and M. LOISELLE, 1980: Comparison between measured and computed concentrations of sulfur compounds in Eastern North America, to appear in Journal of Geophysical Research Procedings of CACGP Symposium on Trace Gases and Aerosols, August 1979.

WISNIEWSKI, J. and KEITZ, L., 1980: The magnitude of the acid rain problem from a monitoring viewpoint within the continental U.S. (submitted to *Science*).

Appendix 1

Work Group 2

Terms of Reference
and Additional Guidance

Terms of Reference from the MOI

The Group will provide information based on cooperative atmospheric modeling activities leading to an understanding of the transport of air pollutants between source regions and sensitive areas, and prepare proposals for the "Research, Modeling and Monitoring" element of an agreement. As a first priority the Group will by October 1, 1980 provide initial guidance on suitable atmospheric transport models to be used in preliminary assessment activities.

In carrying out its work, the Group will:*

- identify source regions and applicable emission data bases;
- evaluate and select atmospheric transport models and data bases to be used,
- relate emissions from the source regions to loadings in each identified sensitive area;
- calculate emission reductions required from source regions to achieve proposed reductions in air pollutant concentration and deposition rates which would be necessary in order to protect sensitive areas;

---

* proposed additional term of reference:
" - evaluate and employ available field measurements, monitoring data and other information;"

- assess historic trends of emissions, ambient concentrations and atmospheric deposition to gain further insights into source-receptor relationships for air quality, including deposition; and
- prepare proposals for the "Research, Modeling and Monitoring" element of an agreement.

Additional Guidance from the Chairman of WG 3B

Each Work Group will be responsible individually for the following.

a. Develop data needs and analysis methods for their Work Group; identify required inputs from other Work Groups; (due to the size of the Work Groups, the Chairmen will have to very carefully orchestrate the Group's activities in order to accomplish their tasks).

b. The technical review (including peer review as necessary) of their work products.

c. Maintaining agreed upon work schedules with prompt notification to 3A Chairman in the event of any significant deviation from Work Plan.

d. Responsible for coordination with their counterparts from the other country in conducting full cooperative analyses in order to fulfill the terms of reference.

e. Responsible for fulfilling requests for information from other work groups in a timely fashion.

f. Be prepared to draft language for portion of agreement that pertains to their tasks as directed by Coordinating Committee.

Appendix 2

Membership of Work Group 2

1. United States

Chairman:
Lester Machta, Director
Air Resources Laboratory
NOAA Room 613
8060 13th Street
Silver Spring, MD 20910

Vice Chairman:
Lowell Smith, Director
Program Integration and Policy Staff
U.S. EPA RD-681
Washington, D. C. 20460

Members:
Paul Altshuller
Environmental Sciences Research
Laboratory
Environmental Protection Agency
Research Triangle Park, NC 27711

Franz Burmann
Environmental Monitoring Systems
Laboratory
Environmental Protection Agency
Research Triangle Park, NC 27711

Robert Kane
Department of Energy
Office of Regulatory Affairs EV-21
1000 Independence Avenue, S. W.
Washington, D. C. 20585

Roger Morris
Department of Energy
Office of Policy and Evaluation PE-83
1000 Independence Avenue, S.W.
Washington, D. C. 20585

Bernard Silverman
Water and Power Resources Services
E & R Center P. O. Box 25007
Department of Interior
Bldg. 67 - Denver Federal Center
Denver, CO 80225

Alternate for Siverman

Richard Ives
Department of Interior, Code 124
Washington, D.C. 20240

Yeh Kung-Wei
Council of Environmental Quality
722 Jackson Place, N. W.
Washington, D. C. 20006

Ken Demerjian
Environmental Sciences Research Laboratory
Environmental Protection Agency
Research Triange Park, NC 27711

Dan Golomb
Office of Environmental Processes and
Effects Research RD-682
Environmental Protection Agency
Washington, DC 20460

Brand Niemann
Program Integration and Policy Staff
Environmental Protection Agency
Washington, DC 20460

Joe Tikvart
Office of Quality Planning and Standards
Environmental Protection Agency
Research Triangle Park, NC 27711

John Miller
Air Resources Laboratories
National Oceanic and Atmospheric Administration
8060 13th Street
Silver Spring, MD. 20910

Jack Blanchard
OES/ENH Room 7820
State Department
2101 C Street, N. W.
Washington, DC 20520

Liaison: Robin Porter
Department of State
EUR/CAN, Room 5227
2101 C Street, N.W .
Washington, DC 20520

Conrad Kleveno
Office of International Activities
Environmental Protection Agency
Washington, DC 20460

2. Canada

Chairman:

Howard Ferguson, Director
Air Quality and Inter-environmental Research Branch
Atmospheric Environment Service
4905 Dufferin Street
Downsview, Ontario M3H5T4

Vice Chairman:

Greg Van Volkenburgh, Supervisor
Technology Development and Appraisal Section
Air Resources Branch
Ontario Ministry of the Environment
880 Bay Street, 4th Floor
Toronto, Ontario, M551Z8

Members:

Douglas M. Whelpdale
Air Quality and Inter-environmental Research Branch
Atmospheric Environment Service
Environment Canada
4905 Dufferin Street
Downsview, Ontario, M3H5T4

James W.S. Young
Air Quality and Inter-environmental Research Branch
Atmospheric Environment Service
Environment Canada
4905 Dufferin Street
Downsview, Ontario, M3H5T4

Marvin P. Olson
Air Quality and Inter-environmental Research Branch
Atmospheric Environment Service
Environment Canada
4905 Dufferin Street
Downsview, Ontario M3H5T4

Peter W. Summers
Air Quality and Inter-environmental Research Branch
Atmospheric Environment Service
Environment Canada
4905 Dufferin Street
Downsview, Ontario, M3H5T4

Paul Choquette, Chief
Pollution Data Analysis Division
Environmental Protection Service
Environment Canada
Place Vincent Massey
Ottawa, Ontario, K1A1C8

B. Power
Environmental Management and Control Division
Newfoundland Department of Provincial Affairs and Environment
Elizabeth Towers
St. John's, Newfoundland

G. Paulin
Director de la Recherche
Environnement Quebec
194 ave St-Sacrement
Quebec, P.Q. G1N4J5

A. Venkatram
Air Quality and Meteorology Section
Air Resources Branch
Ontario Ministry of Environment
880 Bay Street, 4th Floor
Toronto, Ontario, M551Z8

Liaison:

R. Beaulieu
United States Transboundary Relations Division
Department of External Affairs
125 Sussex Drive
Ottawa, Ontario, K1AOG2

Hans Martin
LRTAP Liaison Office
Atmospheric Environment Service
4905 Dufferin Street
Downsview, Ontario, M3H5T4

Appendix 3

Glossary of Terms

Introductory Comments

During the preparation of this glossary, use has been made of terminology and definitions found in, *inter alia*, the first two annual reports of the United States-Canada Research Consultation Group on the Long Range Transport of Air Pollutants, and the draft Federal Acid Rain Assessment Plan. An obvious need exists for uniformity in terminology amongst all Work Groups and others involved in activities related to the Memorandum of Intent and subsequent developments. It is anticipated that this glossary will grow and be refined as further contributions from specialists in various disciplines are received.

Acid Deposition: Collectively, the processes by which acidic and acidifying materials are removed from the atmosphere and deposited at the surface of the earth. Also, the amount of material so deposited. (Units: $ML^{-2}T^{-1}$.)

Acid Precipitation: A more precise term than acid rain, it usually refers to all types of precipitation with pH less than 5.6.

Acid Rain: A popular term used to describe precipitation that is more acidic than "clean" rain ($pH \sim 5.6$). It is also used more generally to describe other atmospheric deposition phenomena involving acidity.

Analytical Model: A mathematical model in which the solution to the system of governing equations is expressed in terms of analytical functions. As such, these models are simplifications of Lagrangian, Eulerian or statistical models.

Anthropogenic: Produced by man's activity.

Bulk Deposition: The term applied to atmospheric deposition collected in a collector which is open at all times. Bulk deposition consists of wet deposition, plus an unknown fraction of the dry particulate deposition, plus an unknown and probably very small fraction of the dry gaseous deposition.

Dry Deposition: Collectively, the processes, excluding precipitation processes, by which materials are removed from the atmosphere and deposited at the surface of the earth. Processes include sedimentation of large particles, the turbulent transfer to the surface of small particles and gases, followed, respectively, by impaction and sorption or reaction. Also, the amount of material so deposited. (Units: $ML^{-2}T^{-1}$.)

Ensemble Mean: The average over a number of individual model runs in which only one or a few adjustable parameters are allowed to change.

Eulerian Model: A mathematical model in which computations are made successively at fixed points in space (as opposed to Lagrangian models where computations are made following an air parcel). Computation points are usually arranged in a fixed grid, and the model is also known as a grid model.

Flux: A physical quantity, the amount (mass) of material passing through a unit area in a unit of time. (Units: $ML^{-2}T^{-1}$.)

Individual Realization: The result from a single model run with a given set of input parameters.

Inventory: A listing of emission source strengths of a particular pollutant for a specified time period. Inventories and parameters are normally organized on a point-source basis, an area-source basis, or a combination of the two. Area sources may be represented on a grid, urban-area, county, state, province, or national basis.

Isopleth: A line drawn on a field of values which joins points of equal value in time or space.

Lagrangian Model: A mathematical model in which computations are made successively in the same air parcel(s) as it moves along a trajectory. Because this type of model is based on following an air parcel, it is also known as a trajectory model.

Loading (atmospheric): The amount of a pollutant in the atmosphere expressed in mass or concentration units. (May also be expressed on a per unit time and/or area basis.)

Loading Surface: A term used interchangeably with deposition.

LRTAP: The long-range transport of air pollutants refers to the processes, collectively, by which pollutants are transported, transformed and deposited, on a regional scale (of the order of hundreds to thousands of km).

Mb (Millibar) Level: A surface of constant pressure in the atmosphere, identified by the pressure expressed in mb. (Common pressure levels used in air quality modeling are 925 and 850 mb levels.)

Mixing Height: The height above the earth's surface of a boundary layer inversion which is usually the upper limit of turbulent mixing activity, and which inhibits upward flux of pollutant.

Model: A quantitative simulation of the behaviour of a portion of the environment.

Model Evaluation: A procedure by which the validity and sensitivity of a model is assessed. Usually the validity is ascertained by comparing model outputs with measurements, and the sensitivity assessed through a series of model runs in which input parameter values are altered in sequence, and the results intercompared.

Model Intercomparison: A procedure of comparing the results of several models which have been run on specified data bases and with (usually) specified values of model parameters.

Model Resolution: The ability of a model to distinguish (utilize) small spatial or temporal changes in input variables.

Model Sensitivity: A model characteristic which is described by the response of an output parameter to a unit change in an input variable or a model parameter.

Model Validation: The part of model evaluation in which modeled results are compared with measured values.

Oxides of Nitrogen: This term usually denotes the sum of nitric oxide (NO) and nitrogen dioxide (NO_2). Other forms are nitrate (NO_3), nitrous oxide (N_2O), and dinitrogen pentoxide (N_2O_5).

Oxides of Sulfur: This term usually denotes sulfur dioxide (SO_2). Other forms are sulfur trioxide (SO_3) which is uncommon, and sulfate (SO_4).

Parameterization: The representation of a physical, chemical or other process by a convenient mathematical expression containing quantities (parameters) for which measurements or estimates are usually available.

Receptor: An organism, ecosystem or object which is the direct or indirect recipient of atmospheric deposition.

Scavenging: The processes by which materials are incorporated into precipitation elements and (usually) brought to the earth's surface.

Scenario: In the modeling context, a set of specified conditions (usually emissions inventory) for input to the model which usually reflect some anticipated future situation (e.g., energy use or pollution emissions).

Sensitive Area: A geographical area in which a receptor (or receptors) exhibit damage in response to a (pollution-imposed) stress.

Sensitivity Receptor: The degree to which a receptor exhibits an adverse effect from a (pollution-imposed) stress.

Source-Receptor Relationship: An expression of how a pollution-source area and a receptor region are quantitatively linked.

Spatial Resolution: The minimum distance in space over which meaningful differences in results can be determined (using a particular model.) (For example, a model based on a 381-km grid will provide no significantly different information for two receptor points separated by less than approximately 381 km.)

Statistical Model: A mathematical model which uses statistical values of parameters as inputs for the computations.

Surrogate: The term applied to a parameter which is used to represent another. (For example, modeling hydrogen ion behavior in the atmosphere is difficult, so that sulfate ion is used as a substitute.)

Susceptibility: A receptor or receptor area is said to be susceptible if it is both sensitive, and receiving a pollutant loading or stress.

Temporal Resolution: The minimum time during which meaningful differences in results can be determined (using a particular model). (For example, models using upper air data which are only available every six hours are limited in their temporal resolution to about 6 hours.)

Trajectory: The path or track of an air parcel through the atmosphere. It can be calculated from observed or gridded wind data either forward or backward from a point (source or receptor, respectively).

Transfer Matrix: A presentation of source-receptor relationships in a matrix form. Matrix elements can be expressed as percentage values, as absolute values, or as values normalized by source strength.) Such a presentation provides a means of easy comparison of the impact of a variety of sources on a variety of receptors.

Transformation (chemical): The processes by which chemical species are converted into other chemical species (in the atmosphere).

Variance: A measure of variability. It is denoted by σ^2 and defined as the mean-square deviation from the mean, that is, the mean of the squares of the differences between individual values of x and the mean value $\bar{x}$.

$\sigma^2 = E[(x-\bar{x})^2]$, where E denotes the expected value.

Wet Deposition: Collectively, the processes by which materials are removed from the atmosphere and deposited at the surface of the earth by precipitation elements. The processes include in-cloud and below-cloud scavenging of both gaseous and particulate materials. Also, the amount of material so deposited. (Units: $ML^{-2}T^{-1}$.)

Appendix 4

Inventory of Available Models

Table 1. Summary of Principal Regional Air Quality Simulation Models in the United States and Canada

Name of Organization	Model Acronym	Type of Model	Time Period	Principal References
Batelle-Pacific Northwest Labs	RAPT	Lagrangian	monthly to annual	McNaughton (1980)
Brookhaven National Labs	AIRSOX	Lagrangian	monthly to annual	Kleinman et al (1980)
Argonne National Labs	ASTRAP*	Lagrangian	monthly to annual	Shannon (1980)
ERT, Inc.	SURAD	Eulerian	episodes	Lavery et al (1980)
ERT, Inc.	MESOPUFF	Lagrangian	episodes	Bass (1980)
Teknekron Research, Inc.	RCDM*	Analytical Eulerian	annual	Fay and Rosenzweig (1980) Niemann et al (1980)
Teknekron Research, Inc.	REGMOD	Eulerian	episodes	Prahm and Christensen (1977) Niemann et al (1980)
Washington University	CAPITA-Monte Carlo	Statistical Lagrangian	monthly to annual	Patterson et al (1980)
SRI International	ENAMAP-1*	Lagrangian	monthly to annual	Bhumralkar et al (1980)
EPA Meterology Lab	RPAQSM	Eulerian	episodes	Lamb (1980)
Atmospheric Environ. Service	AES-LRT*	Lagrangian	monthly to annual	Voldner et al (1980)
Ministry of the Environment	OME-LRT*	Statistical Lagrangian	annual	Venkatram et al (1980)
NOAA/ARL	ATAD	Lagrangian	monthly	Heffter (1980)
Colorado State University	RADM	Lagrangian	monthly	Henmi (1980)
University of Wisconsin	ATM-SOX	Statistical Eulerian	monthly	Wilkening and Ragland (1980)
MEP, Ltd.	LRT	Lagrangian	seasonal	Weisman (1980)
Environnement Québec	TGD-EQ	Statistical Lagrangian	seasonal to annual	Lelièvre (1981)

* Models selected for use by Work Group 2 as of January 15, 1981.

BASS, A., 1980: Modeling long-range transport and diffusion. Preprint, Proceedings of the Second Joint AMS/APAC Conference on Applications of Air Pollution Meteorology, March 24-27, 1980, New Orleans, LA.

BHUMRALKAR, C.M.., W.B. JOHNSON, R.L. MANCUSCO, R.H. THUILLIER, and D.E. WOLF, 1980: Interregional exchanges of airborne sulfur pollution and deposition in Eastern North America, Proceedings of the Second Joint AMS/APCA Conference on Applications of Air Pollution Meteorology, March 24-27, New Orleans, LA.

FAY, J.A.. and ROSENZWEIG, J.J., 1980: An Analytical Diffusion Model for Long Distance Transport of Air Pollutants. Atmospheric Environment, vol. 14, 355-365.

HEFFTER, J.L., 1980: Transport layer depth calculations, paper in Proceedings of the Second Joint AMS/APCA Conference on Air Pollution Meterology, March 24-27, New Orleans, LA.

HENMI, J., 1980: Long-Range Transport Model of SO2 and Sulfate and its Application to the Eastern United States, Journal of Geophysical Research, 85, C8, 4436 - 4442, August 20.

KLEINMAN, L.J., J.G. CARNEY, and R.E. MEYERS, 1980: Time Dependence on Averge Regional Sulfur Oxide Concentrations, Proceedings of the Second Joint AMS/APCA Conference on Applications of Air Pollution Meteorology, March 24-27, New Orleans, LA.

LAMB, R.G., 1980: A Regional Scale (1000 km) Model of Photochemical Air Pollution - Part I: Theoretical Formulation, draft report from the Meteorology and Assessment Division, EPA Environmental Sciences Laboratory, Research Triangle Park, N.C.

LAVERY, T.L., et al, 1980: Development and validation of a regional model to simulate atmospheric concentrations of sulfur dioxide and sulfate, paper in Proceedings of the Second Joint AMS/APCA Conference on Air Pollution Meteorology, March 24-27, New Orleans, LA, 236-247.

LELIEVRE, C., 1981: Modèle simple de transformation chimique du soufre lors de son transport dans l'atmosphère, Rapport Interne, Service de la Metéorologie, Ministère de l'Environnement du Québec.

McNAUGHTON, D.J., 1980: Time series comparisons of regional model predictions with sulfur oxide observations from the SURE program, Paper 80-54.5 presented at the 73rd Annual Meeting of the Air Pollution Control Association, Montreal, Quebec, June 22-27, 1980.

NIEMANN, B.L., AA. HIRATA, B.R. HALL, M.T. MILLS, P.M. MAYERHOFER and L.F. SMITH, 1980: Initial Evaluation of regional transport and subregional dispersion models for sulfur dioxide and fine particulates, Proceedings of the Second Joint AMS/APCA Conference on Applications of Air Pollution Meteorology, March 24-27, New Orleans, LA.

PATTERSON, D.E., HUSAR, R.B., WILSON, JR., W.E. and SMITH, L.F., 1980: Monte Carlo Simulation of a daily regional sulfur distribution: Comparision with SURE sulfate data and visibility observations during August 1977, Paper submitted to J. Appl. Meteor., June.

PRAHM, L.V. and O. CHRISTENSEN, 1977: Long-range Transmission of Pollutants Simulated by a Two-Dimensional Pseudo-Spectral Dispersion Model, J. Appl. Meteor., 16,9, 896-910.

SHANNON, J., 1980: Examination of surface removal and horizontal transport of atmospheric sulfur on a regional scale, Proceedings of the Second Joint AMS/APCA Conference on Applications of Air Pollution Meteorology, March 24-27, New Orleans, LA.

VENKATRAM, A., B.E. LEY, and S.Y. WONG, 1980: A statistical model to estimate long-term concentrations of pollutants associated with long range transport, to appear in Atmospheric Environment.

VOLDNER, E.C., M.P. OLSON, K. OIKAWA, and M. LOISELLE, 1980: Comparision between measured and computed concentrations of sulfur compounds in Eastern North America, to appear in Journal of Geophysical Research Proceedings of CACGP Symposium on Trace Gases and Aerosols, August 1979.

WEISMAN, B., 1980: Long-range transport model for sulfur, Paper 80-54.6 presented at the 73rd Annual Meeting of the Air Pollution Control Association, Montreal, Quebec, June 22-27, 1980.

WILKENING, K.E. and K.W. RAGLAND, 1980: Users Guide for the University of Wisconsin Atmospheric Sulfur Computer Model (UWATM-SOX), draft report prepared for the EPA Environmental Research Laboratory - Duluth, MN, November 12.

Appendix 5

Descriptions of Selected Models

TABLE OF CONTENTS

			PAGE
ASTRAP	-	Parameterizations	A.5-2
	-	Comparisons with Data	A.5-4
ENAMAP-1	-	Parameterizations	A.5-9
	-	Comparisons with Data	A.5-11
AES-LRT	-	Parameterizations	A.5-23
	-	Comparisons with Data	A.5-24
OME-LRT	-	Parameterizations	A.5-29
		Comparisons with Data	A.5-31
RCDM	-	Parameterizations	A.5-34
	-	Comparisons with Data	A.5-35

FIGURE AND TABLE DESCRIPTIONS

			Page
Figure	A5-1	Comparison of cumulative sulfate in rain, expressed as total sulfur for 1977 with ASTRAP simulations (isopleths) (Galloway and Whelpdale).	A.5-6
Figure	A5-2	Comparison of Jan-Feb 1978 SURE average sulfate measurements (number) with ASTRAP simulations (isopleths) using Jan-Feb 1975 meteorology. (Shannon)	A.5-7
Figure	A5-3	Comparison of August 1977 SURE average sulfate measurements (numbers) with ASTRAP simulations (isopleths) using July-August 1975 meteoroglogy. (Shannon)	A.5-8
Figure	A5-4	SO_2 concentrations (ug/m^3) for January 1977 from ENAMAP-1	A.5-12
Figure	A5-5	SO_4 concentrations (ug/m^3) for January 1977 from ENAMAP-1	A.5-13
Figure	A5-6	SO_2 concentrations (ug/m^3) for April 1977 from ENAMAP-1	A.5-14
Figure	A5-7	SO_4 concentrations (ug/m^3) for April 1977 from ENAMAP-1	A.5-15
Figure	A5-8	SO_2 concentrations (ug/m^3) for August 1977 from ENAMAP-1	A.5-16
Figure	A5-9	SO_4 concentrations (ug/m^3) for August 1977 from ENAMAP-1	A.5-17
Figure	A5-10	SO_2 concentrations (ug/m^3) for October 1977 from ENAMAP-1	A.5-18
Figure	A5-11	SO_4 concentrations (ug/m^3) for October 1977 from ENAMAP-1	A.5-19
Figure	A5-12	Calculated annual concentrations of SO_2 and SO_4 (ug/m^3) for 1977 from ENAMAP-1	A.5-20
Figure	A5-13	Calculated annual dry and wet depositions of SO_2 ($10\ mg/m^2$) for 1977 from ENAMAP-1	A.5-21

Figure A5-14 Calculated annual dry and wet depositions of SO_4 (10 mg/m^2) for 1977 from ENAMAP-1 A.5-22

Figure A5-15 AES-LRT computed and measured daily mean SO_2 concentrations during October 1977 at Albany, N.Y. (measured-solid, computed-dashed) A.5-25

Figure A5-16 AES-LRT computed and measured daily mean sulfate concentrations during October 1977 at Port Huron, Mich. (measured-solid, computed-dashed) A.5-26

Figure A5-17 Ratios of AES-LRT computed to measured monthly precipitation weighted sulfate concentrations in the rain and percent contribution from direct sulfate scavenging (in parentheses) for October 1977. A.5-27

Figure A5-18 Ratios of AES-LRT computed to measured monthly mean sulfate concentrations in the air for October 1977 A.5-28

Figure A5-19 OME-LRT model predictions of annual wet deposition of sulfur in gm/m^2/year. Stars in figure correspond to monitors in the CANSAP and U.S. networks. Numbers next to stars are station codes referred to in Table A5-1 A.5-32

Table A5-1 Comparison of OME-LRT model predictions with observations of wet deposition of sulfur for 1977 (Galloway and Whelpdale, 1980). A.5-33

Figure A5-20 Isopleths of annual SO_2 concentrations (ug/m^3) simulated by the RCDM A.5-38

Figure A5-21 Isopleths of annual sulfate concentrations (ug/m^3) simulated by the RCDM A.5-39

Figure A5-22 Three-year average (1975-1977) of AQCR average sulfate concentrations (ug/m^3) A.5-40

Figure A5-23 Annual average sulfate concentrations (ug/m^3) at Ontario Hydro monitors in 1978 A.5-41

Figure A5-24 "Annual average" sulfate concentrations (ug/m^3) at the SURE monitors A.5-42

Figure A5-25 Isopleths of wet sulfur deposition (g/m^2yr) simulated by the RCDM A.5-43

Figure A5-26 Wet sulfur deposition (g/m^2yr) at event monitoring sites in the northeastern U.S. (1976-1979) A.5-44

Model: ASTRAP (Advanced Statistical Trajectory Regional Air Pollution Control Model)

Modeling Group: Argonne National Laboratory, Jack Shannon

Model Type: Statistical Lagrangian

Emission Data: Point Sources or gridded virtual sources for a normalized 60 x 60 transition matrix (emission height can be variable)

Wind Data: uses 1/2 NMC* (191 km). Calculate mean transport speed and direction from surface to 1800 metres summer (1000 m. winter) for each Rawinsonde Station. Use inverse distance squared to get value at grid point (starting at radius = 381 km and increase until at least two observing stations).

Precipitation Data: 6 hour amount within 1/4 NMC grid square (95 km). Used average precipitation from those reporting precipitation, within a 1/4 square, and those reporting zero to assign percentage removed (i.e. 3 of 5 reporting precipitation means up to 60% removal is allowed).

Mixing Height: not used directly - numerical integration to 2100 metres using a diurnal pattern of growth of a nocturnal stable layer followed by breakup during the day to a maximum afternoon value and repeating on an actual rawinsonde ascent.

Chemistry: first order SO_2/SO_4, with diurnal variation.

---

* National Meteorological Center

Dispersion: - horizontal from Lagrangian simulated tracers in the mean wind field*

- vertical by one-dimensional numerical integration (11 layers)

Removal Processes: Wet and dry deposition of SO_2 and SO_4, diurnal and seasonal variations.

- wet removal rate proportional to 1/2 power of 6-hourly precipitation amount (4 mm in 6 hours removes everything whereas 1 mm/hour removes 50%).

Model Outputs: Long term regional patterns of SO_2 and SO_4 surface concentration and cumulative wet and dry deposition of total S.

Resolution: Monthly and 1/4 of an NMC grid (95 km).

Area of Application: Eastern North America

Parameter Values: Wind/Precipitation - 1975 Summer (July, August)

Winter (Jan., Feb.)

Average VD_{SO2} and SO_4 = 0.4 cm/sec. (summer)

= 0.25 cm/sec. (winter)

Conversion SO_2/SO_4 = 1.1%/hour (summer)

= 0.55%/hour (winter)

---

* calculation done on ensemble parameters only.

Descriptive Material:

Seasonal and diurnal cycles in the deposition velocities of SO_2 and SO_4 produced by vertical mixing and plant stomatal activity are also provided for in the model. Sulfate deposition velocities used are the same order of magnitude as SO_2 velocities rather than an order of magnitude less as in other modeling studies.

Wet removal is taken into account using the scavenging ratio approach. This method relates wet deposition to the ratio of field measurements of concentration of pollutant measured in the air to that measured in rainfall at the same time. Argonne National Laboratory has found that scavenging rates are relatively constant, and sulfur deposition by wet processes is a function of the half power of the amount of precipitation.

The mixed layer is divided into 11 layers for the vertical numerical integration. A wind field is developed at a specified level in the atmosphere based on NWS data. Winds are interpolated between data points using a radius of influence inverse square relationship.

Comparisons With Data:

The model results were compared with measurements from the SURE data network for 1977 and 1978. The average two-month summer and winter sulfate fields show there are major discrepencies, particularly in the western part of the eastern

U.S. It must be kept in mind, however, that meteorology for a different year was used in the model. The ASTRAP simulations of wet deposition of total sulfur were scaled to a one-year period and compared with observations during 1977 of annual accumulations of sulfate in precipitation, expressed as total sulfur. There is some general agreement, but the data shows a more complex distribution than that indicated by the ASTRAP model results. On an annual basis, an estimated 5.4 million metric tons were deposited on the eastern United States. Wet and dry removal were approximately equally important. By season, dry deposition was equal to wet deposition in the summer, but wet removal was approximately twice dry removal in the winter.

Figures A5-1 through A5-3 show output from the ASTRAP Model.

Figure A5-1 Comparison of cumulative sulfate in rain, expressed as total sulfur for 1977 with ASTRAP simulations (isopleths) (Galloway and Whelpdale).

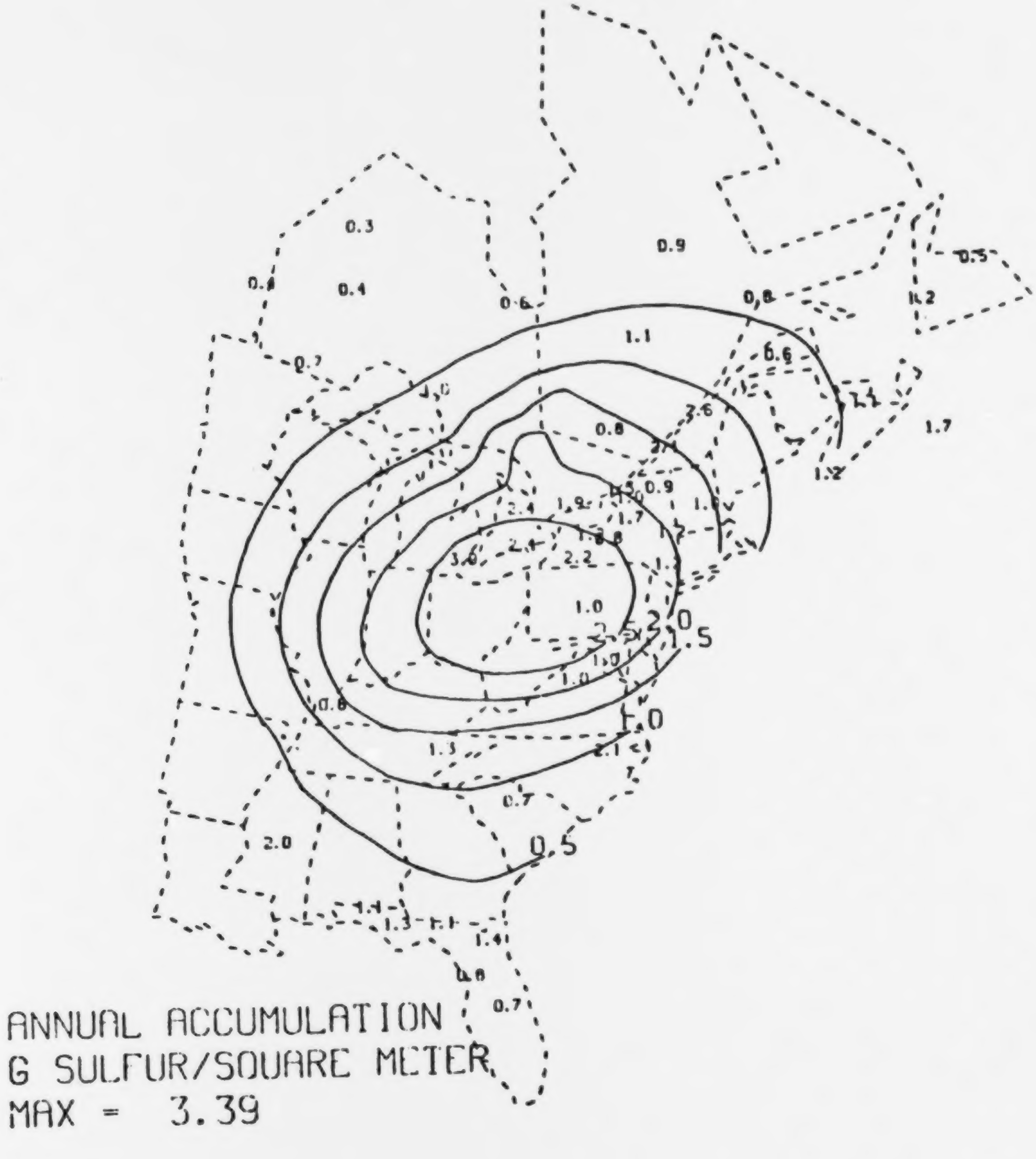

ANNUAL ACCUMULATION
G SULFUR/SQUARE METER
MAX = 3.39
0.5
1.0
1.5
2.0
2.5
0.3
0.4
0.6
0.9
0.8
1.2
1.1
1.7
1.3
0.7
2.0
3.0
2.2

Figure A5-2 Comparison of Jan-Feb 1978 SURE average sulfate measurements (number) with ASTRAP simulations (isopleths) using Jan-Feb 1975 meteorology. (Shannon)

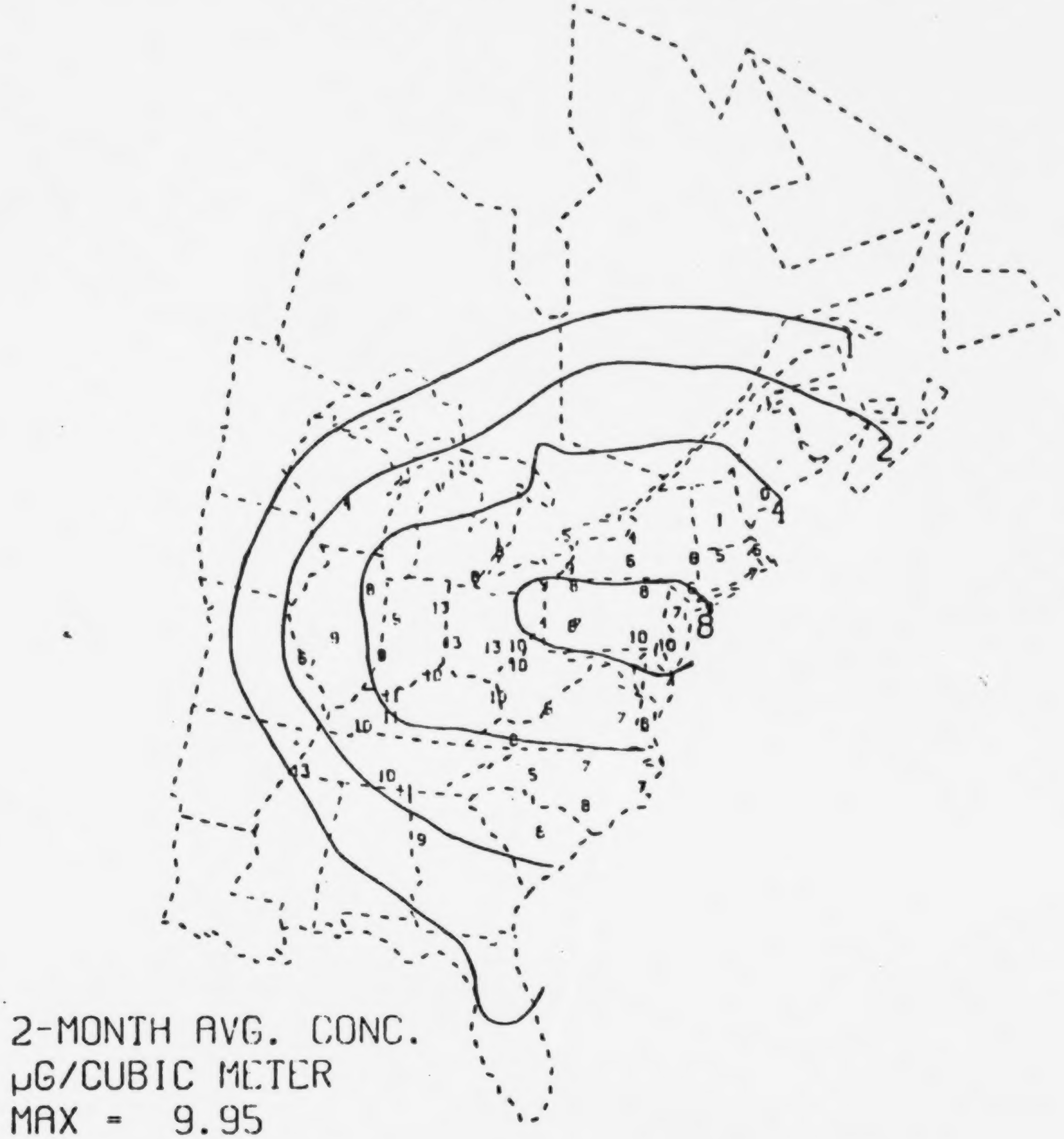
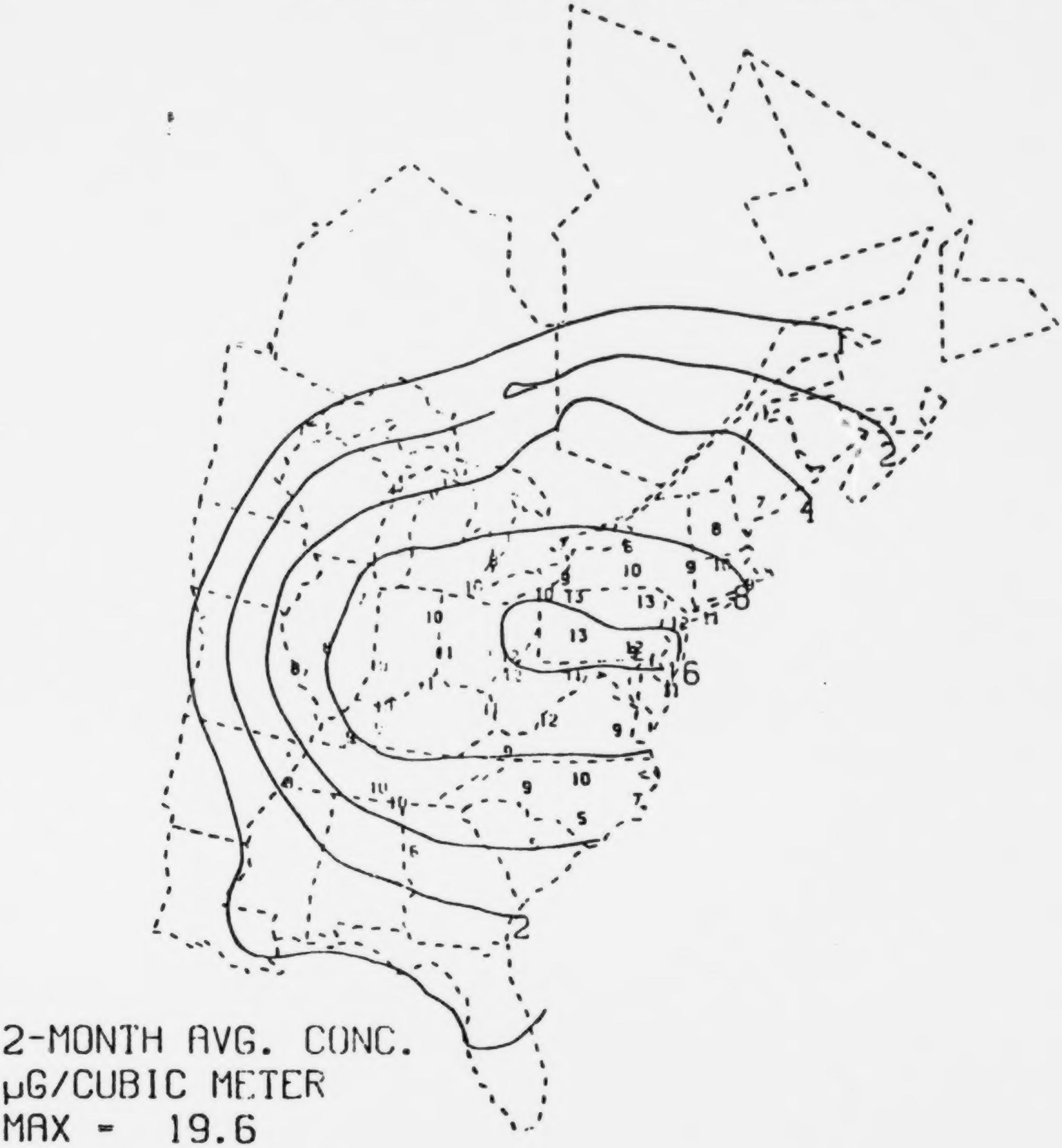

2
4
8
2-MONTH AVG. CONC.
µG/CUBIC METER
MAX = 9.95

Figure A5-3 Comparison of August 1977 SURE average sulfate measurements (numbers) with ASTRAP simulations (isopleths) using July-August 1975 meteoroglogy. (Shannon)


2
7
4
8
10
9
10
13
8
13
12
16
10
11
12
9
9
10
7
5
2
2-MONTH AVG. CONC.
μG/CUBIC METER
MAX = 19.6

Model: ENAMAP-1 (Eastern North America Model of Air Pollution)

Modeling Group: SRI International, Chandrakant Bhumralker and EPA/ESRL, Ken Demerjian

Model Type: Lagrangian Puff

Emission Data:
- 80 km x 80 km UTM SURE grid extended
- SURE and NEDS
- average (annual and seasonal)
- 12 hour puff

Wind Data: historical (retaining original temporal and spatial detail) (1977)
- 3 hour time steps using objectively* analyzed wind fields from surface (6 hour intervals) & upper air data (12 hr. intervals) on 80 x 80 grid.

  $\overline{U} = 0.75\,U$ (850mb); $\overline{\theta} = \theta$ (850mb) - 15°

Precipitation Data: - objectively* analyzed onto 80 x 80 grid using observed data.

Mixing Height: seasonal dependence varying from 1.15 km in winter to 1.45 km in summer.

Chemistry: SO_2/SO_4 first order

Dispersion:
- Fickian ($t^{1/2}$)
- horizontal - uniform
- vertical - mixing (instantaneous) to top of the boundary layer

---

* least squares polynomial fit using at least 3 data points within a radius of influence.

Removal Processes: first order

Model Outputs: (1) SO_2, SO_4 Concentrations
(2) dry and wet deposition
(3) interregional exchanges

Resolution: monthly, 70 x 70 km grid square

Area of Application: Eastern North America

Parameter Values: SO_2/SO_4 1%/hour

$L = 1.3 - 0.15$ km

where   = + 1 in winter; -1 in summer and 0 in spring & fall

SO_2: dry deposition = $0.037\ hr^{-1}$

SO_2: wet deposition = $0.28R\ hr^{-1}$

where R = mm/hr. of precipitation

SO_4 : dry deposition = $0.007\ hr^{-1}$

SO_4 : wet deposition = $0.07R\ hr^{-1}$

Descriptive Material:

ENAMAP-1 was originally developed for the Federal Republic of Germany (as EURMAP-1) and has been adapted to the Eastern North America region and renamed ENAMAP-1.

Upper-air wind data for the U.S. and Canada are provided at the surface and at every 50 mb level (1000, 950, 900, 850, etc.). Therefore, all the winds from the surface up to the mixing heights are used to calculate an average wind. That is, average u and v components are obtained for the boundary layer [surface, h_1, to mixing height, h_I] using the following numerical integration formulas:

$$\overline{u} = \sum_{i=2}^{I} \frac{(u_i + u_{i-1})}{2} * (h_i - h_{i-1}) / \sum_{i=2}^{I} (h_i - h_{i-1}) \tag{A.5-11}$$

$$\overline{v} = \sum_{i=2}^{I} \frac{(v_i + v_{i-1})}{2} * (h_i - h_{i-1}) / \sum_{i=2}^{I} (h_i - h_{i-1})$$

The wind fields are then interpolated every 3 hours between 12-hour data intervals.

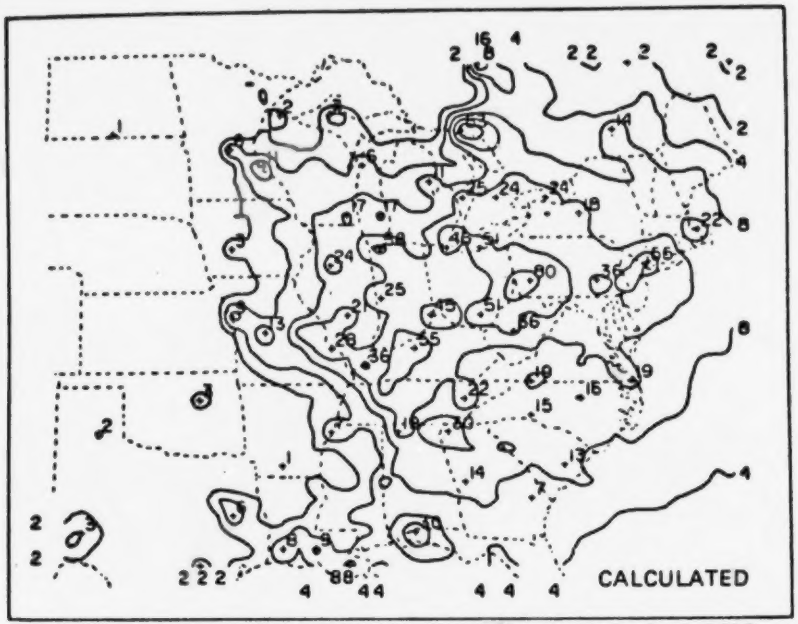
The SO_2 transformation rate, the SO_2 and SO_4 dry deposition velocities and the mixing heights used in the ENAMAP-1 are generally similar to those used in other regional models. The SO_2 and SO_4 wet removal rates are different than those used in other regional models.

Comparisons with Data:

SO_2 emissions from the SURE program and NEDS were used in ENAMAP-1 model simulations. The months of January and August 1977 were chosen for model evaluation, and the results were compared with SURE and SAROAD air quality data. ENAMAP-1 predicted high sulfate in the northeastern states and relatively low values elsewhere in January 1977. The observed concentration field was similar in the East but measured values were higher than predicted in the Midwest. The model results for August 1977 were in better agreement with observations.

Figures A5-4 through A5-14 are seasonal and annual verification outputs from the ENAMAP-1 Model. Comparisons of modeled SO_4 against observed SURE data show very good agreement.

Figure A5-4 SO_2 concentrations (ug/m^3) for January 1977 from ENAMAP-1


CALCULATED

LOCAL MAXIMUM VALUES SHOWN APPLY AT POINTS MARKED BY PLUS SIGNS

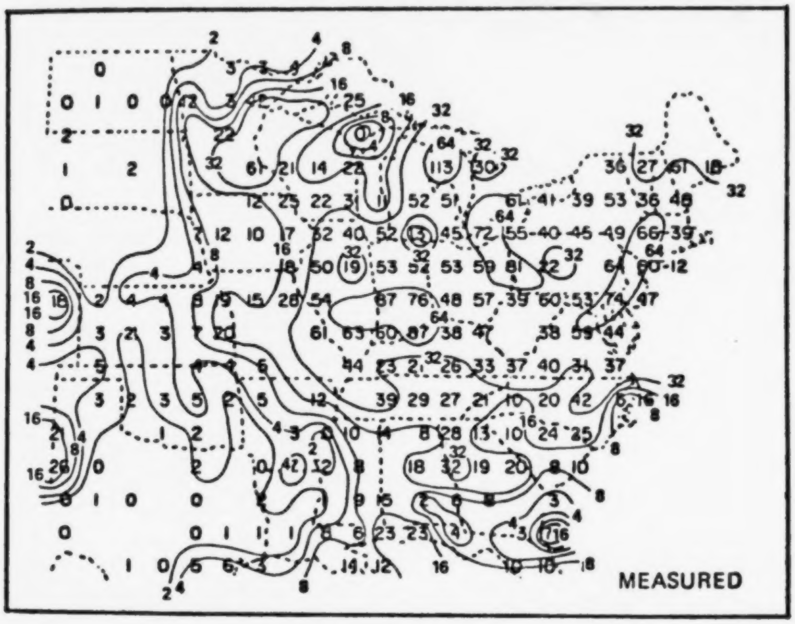
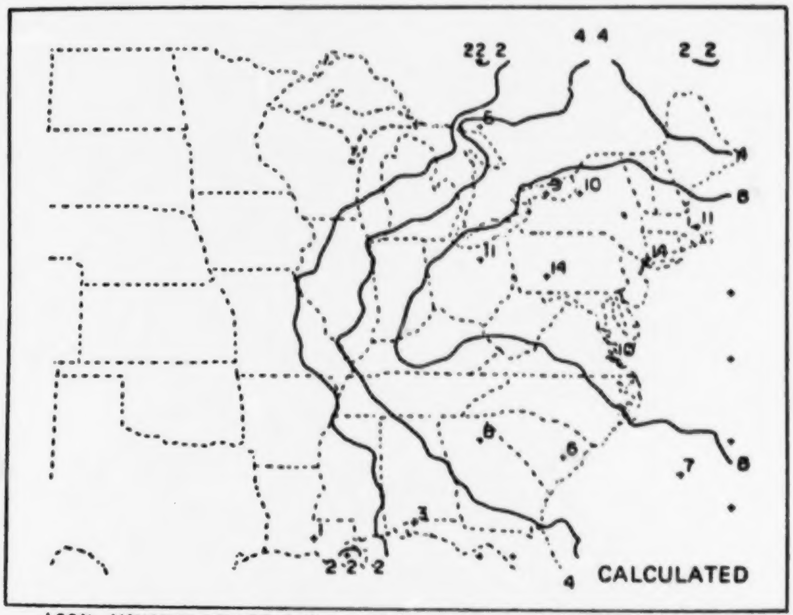


Figure A5-5 SO_4 concentrations (ug/m^3) for January 1977 from ENAMAP-1


CALCULATED

LOCAL MAXIMUM VALUES SHOWN APPLY AT POINTS MARKED BY PLUS SIGNS

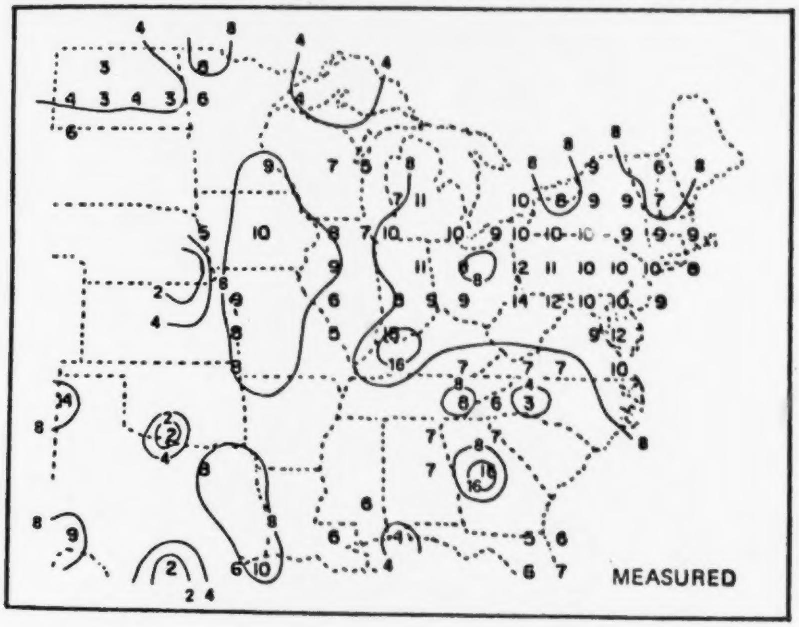
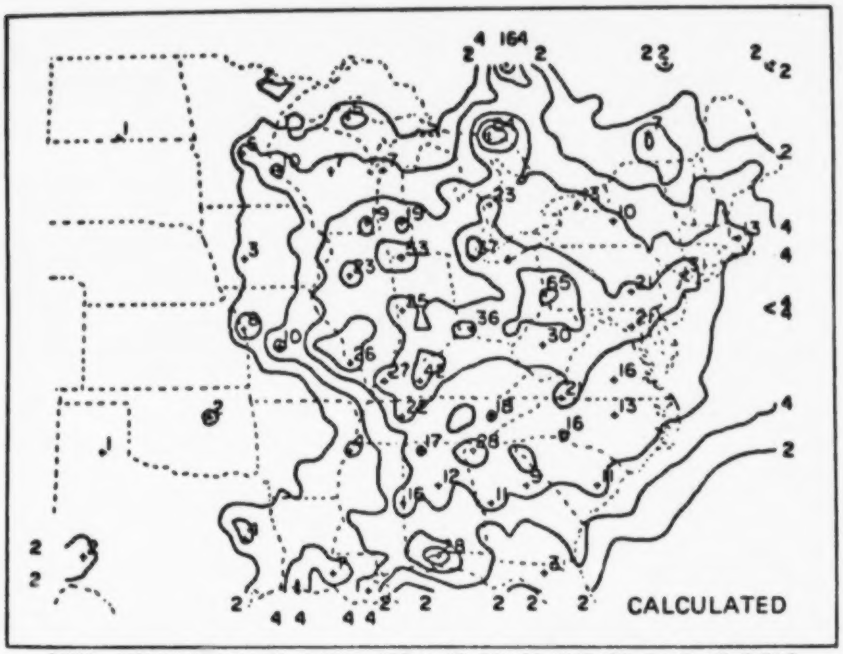


Figure A5-6 SO_2 concentrations (ug/m^3) for April 1977 from ENAMAP-1


CALCULATED

LOCAL MAXIMUM VALUES SHOWN APPLY AT POINTS MARKED BY PLUS SIGNS

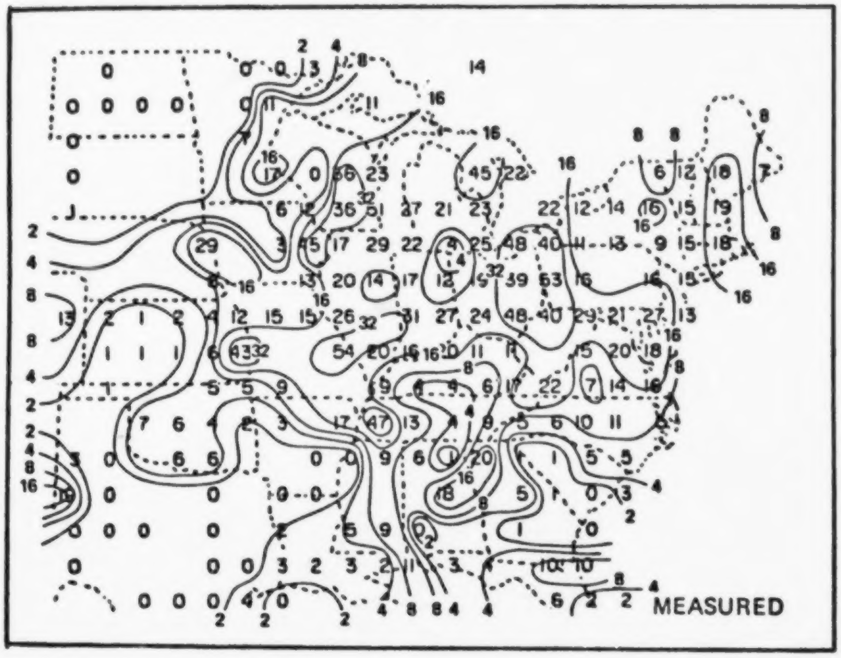
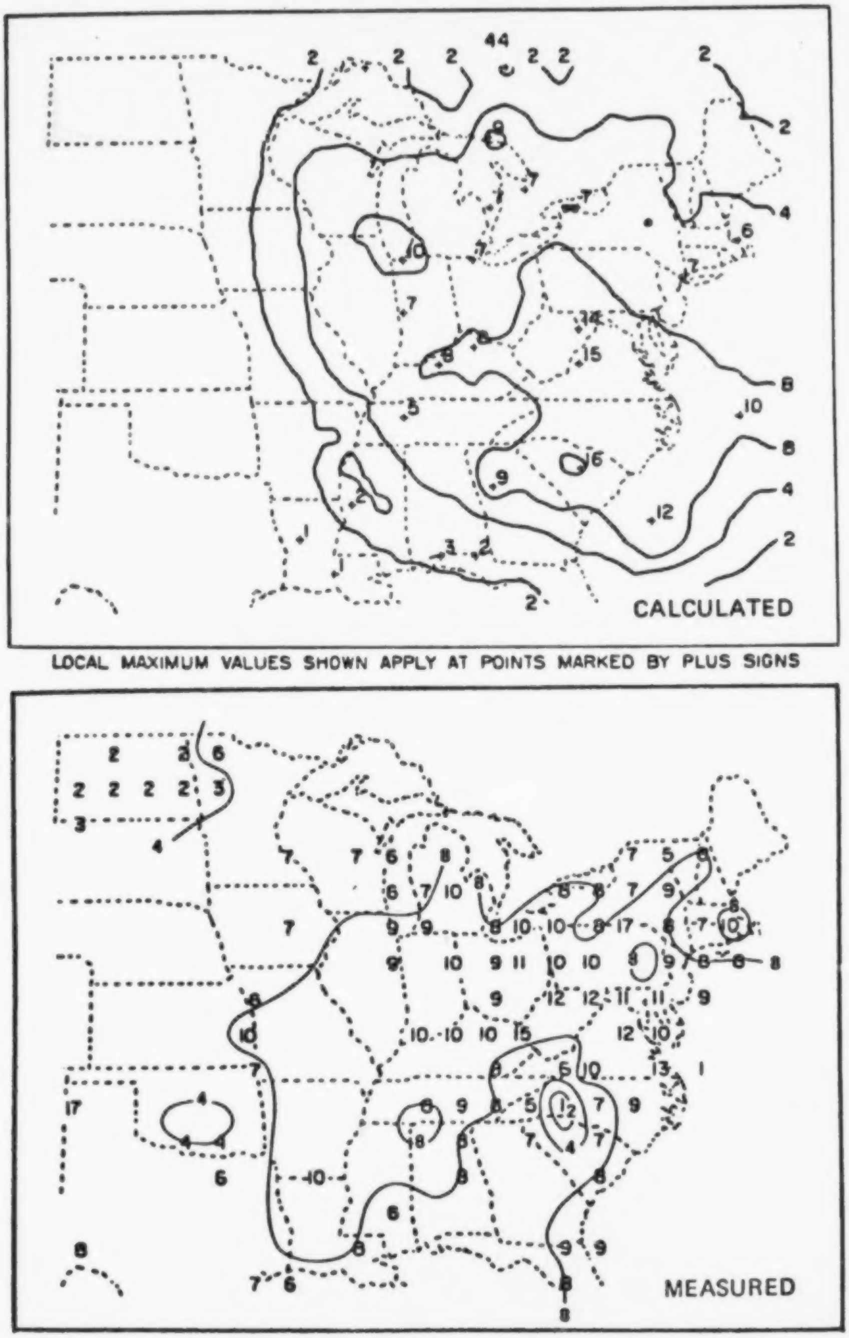
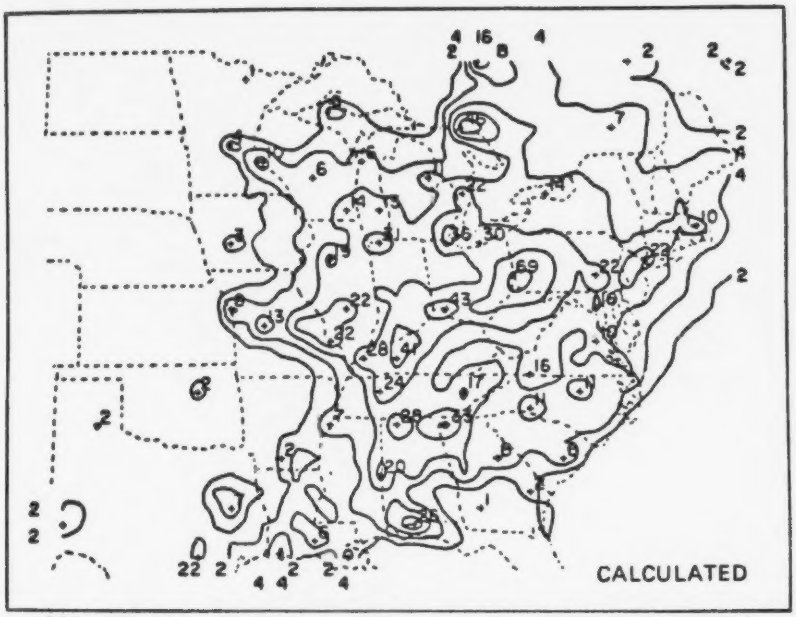


Figure A5-7 SO_4 concentrations (ug/m^3) for April 1977 from ENAMAP-1


CALCULATED
MEASURED

LOCAL MAXIMUM VALUES SHOWN APPLY AT POINTS MARKED BY PLUS SIGNS

Figure A5-8 SO_2 concentrations (ug/m^3) for August 1977 from ENAMAP-1


CALCULATED

LOCAL MAXIMUM VALUES SHOWN APPLY AT POINTS MARKED BY PLUS SIGNS

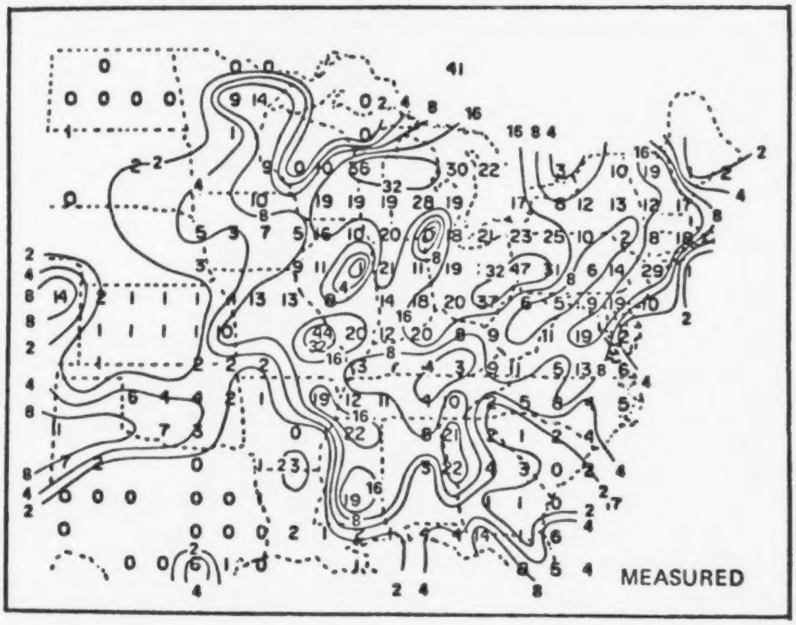


Figure A5-9 SO_4 concentrations (ug/m^3) for August 1977 from ENAMAP-1

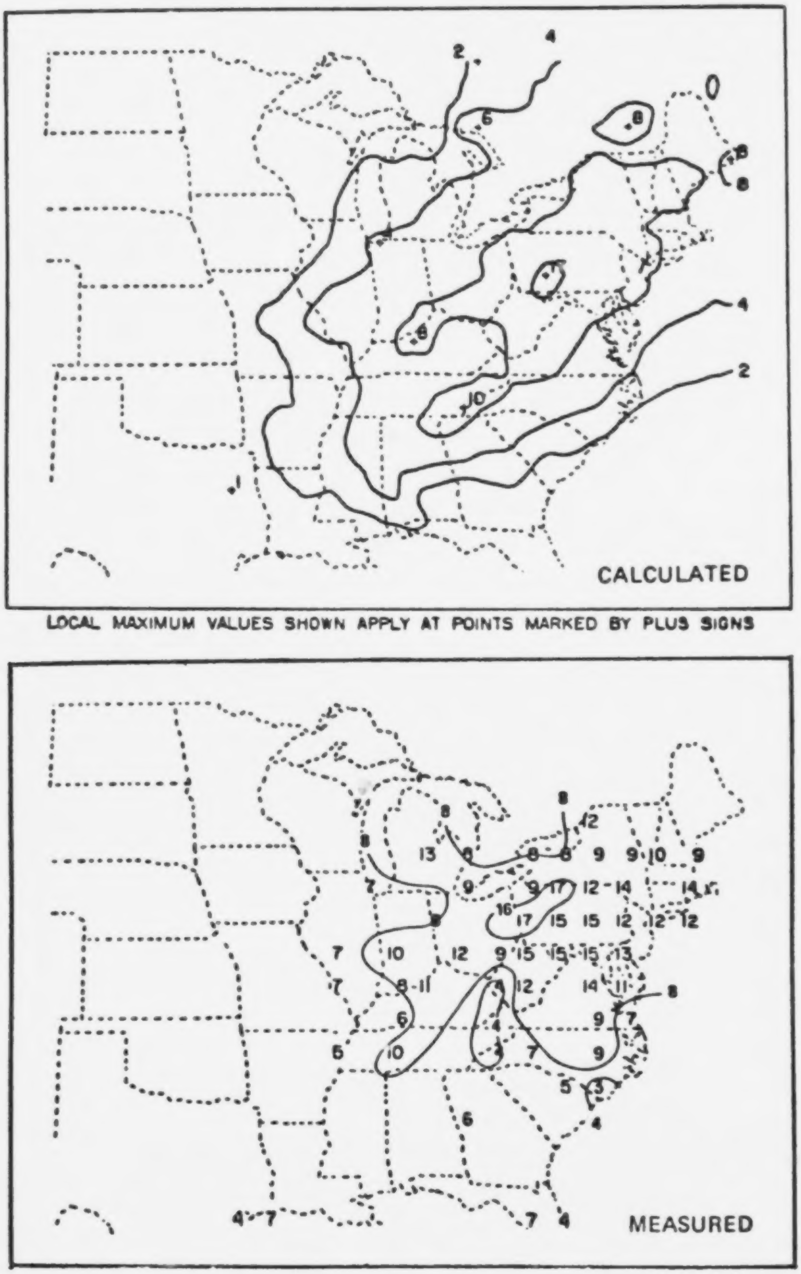
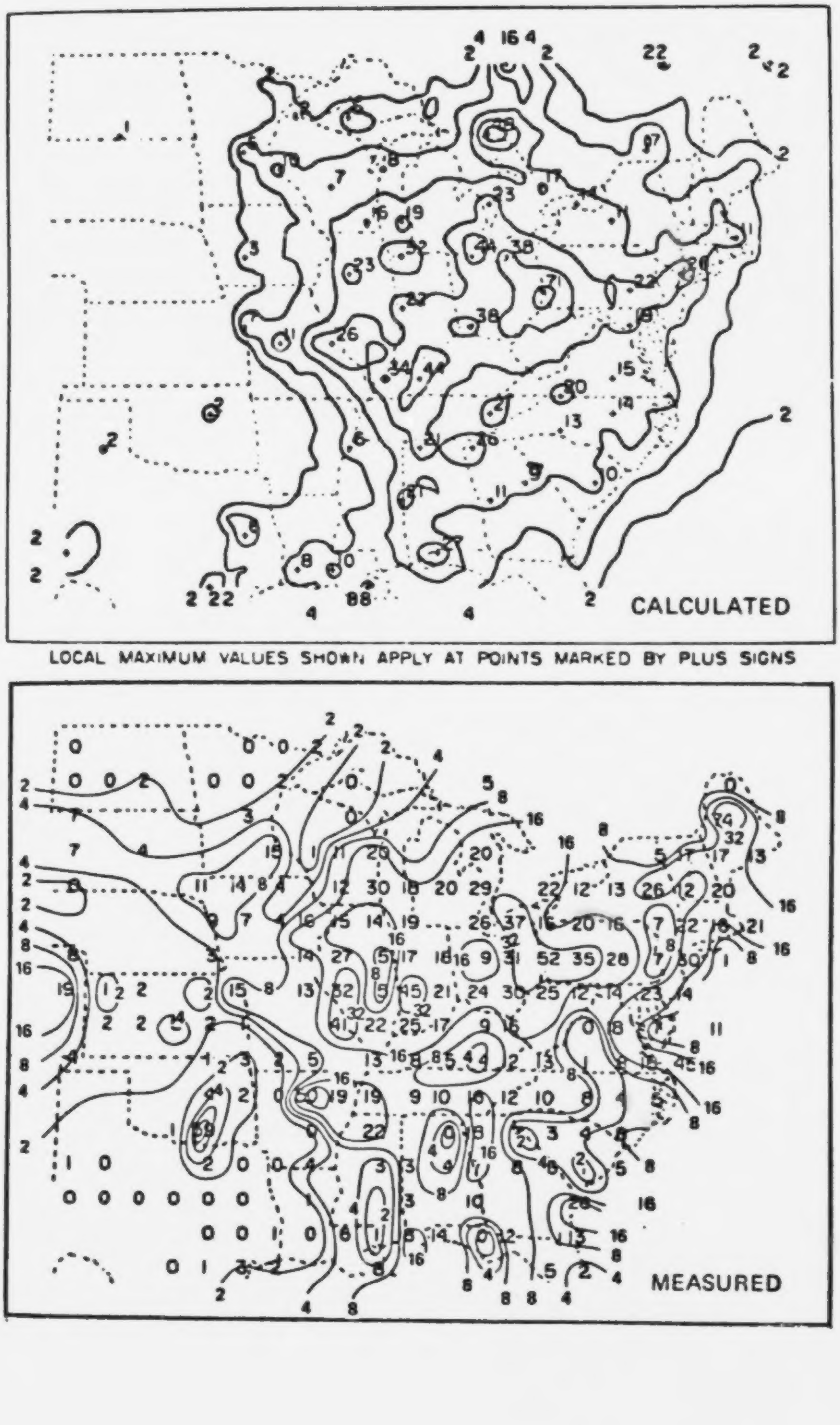
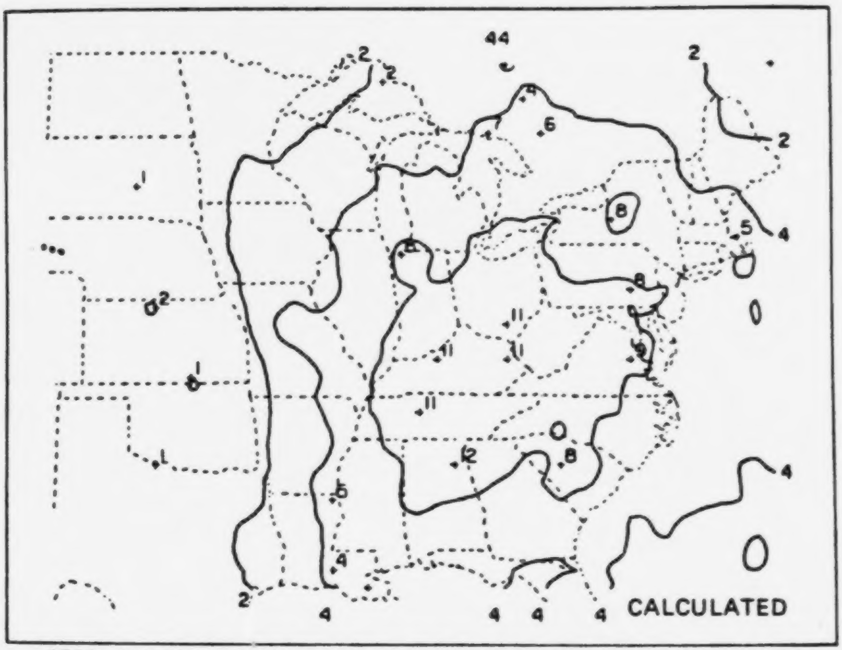

2
4
6
8
8
8
4
2
10
8
1
CALCULATED
LOCAL MAXIMUM VALUES SHOWN APPLY AT POINTS MARKED BY PLUS SIGNS
8
8
12
13
8
8
9
9
10
9
7
9
17
12
14
14
16
17
15
15
12
12
12
7
10
12
9
15
15
15
13
7
8
11
12
14
11
8
6
9
7
6
10
4
7
9
5
3
6
4
4
7
7
4
MEASURED

Figure A5-10 SO$_2$ concentrations (ug/m^3) for October 1977 from ENAMAP-1


CALCULATED
MEASURED

LOCAL MAXIMUM VALUES SHOWN APPLY AT POINTS MARKED BY PLUS SIGNS

Figure A5-11 SO_4 concentrations (ug/m^3) for October 1977 from ENAMAP-1


CALCULATED

LOCAL MAXIMUM VALUES SHOWN APPLY AT POINTS MARKED BY PLUS SIGNS

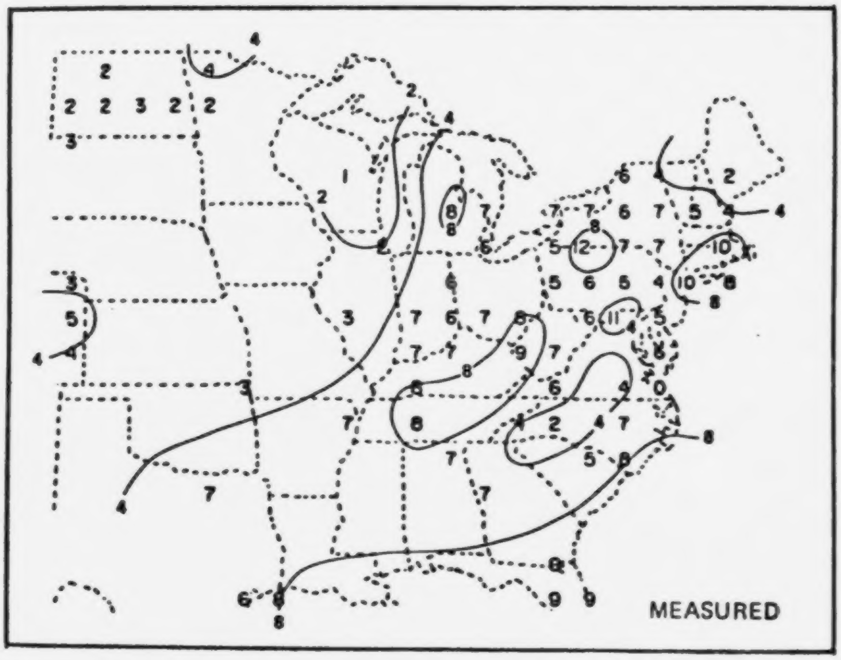
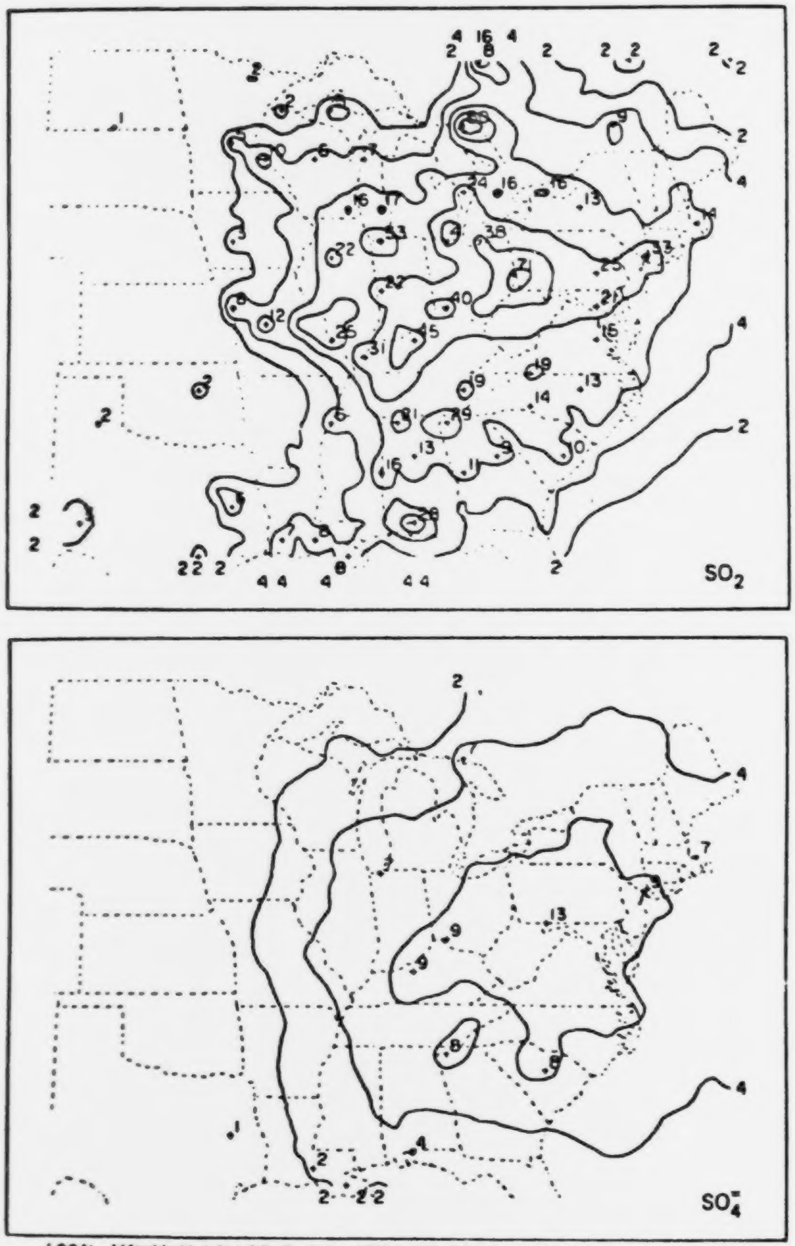
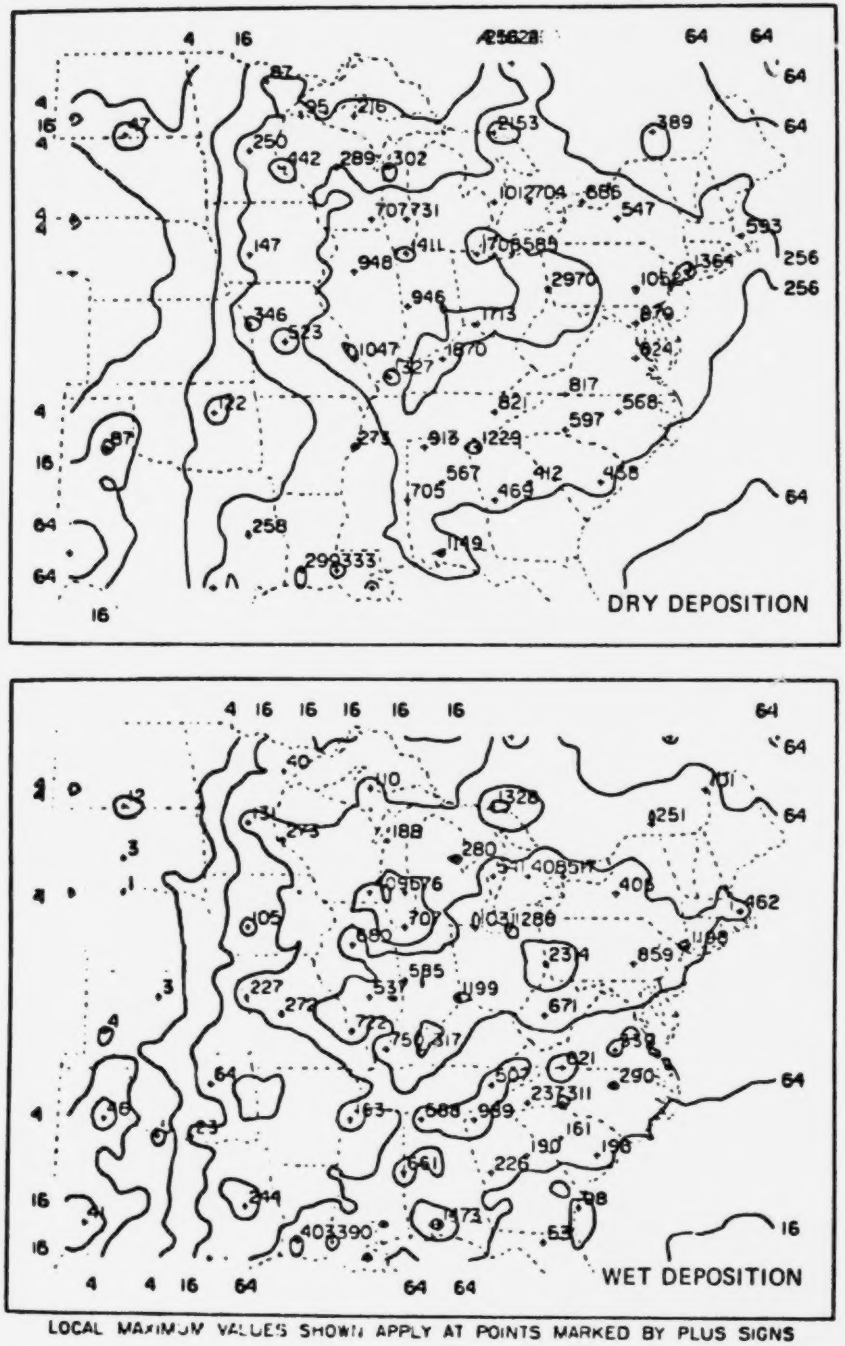


Figure A5-12 Calculated annual concentrations of SO_2 and SO_4 (ug/m^3) for 1977 from ENAMAP-1



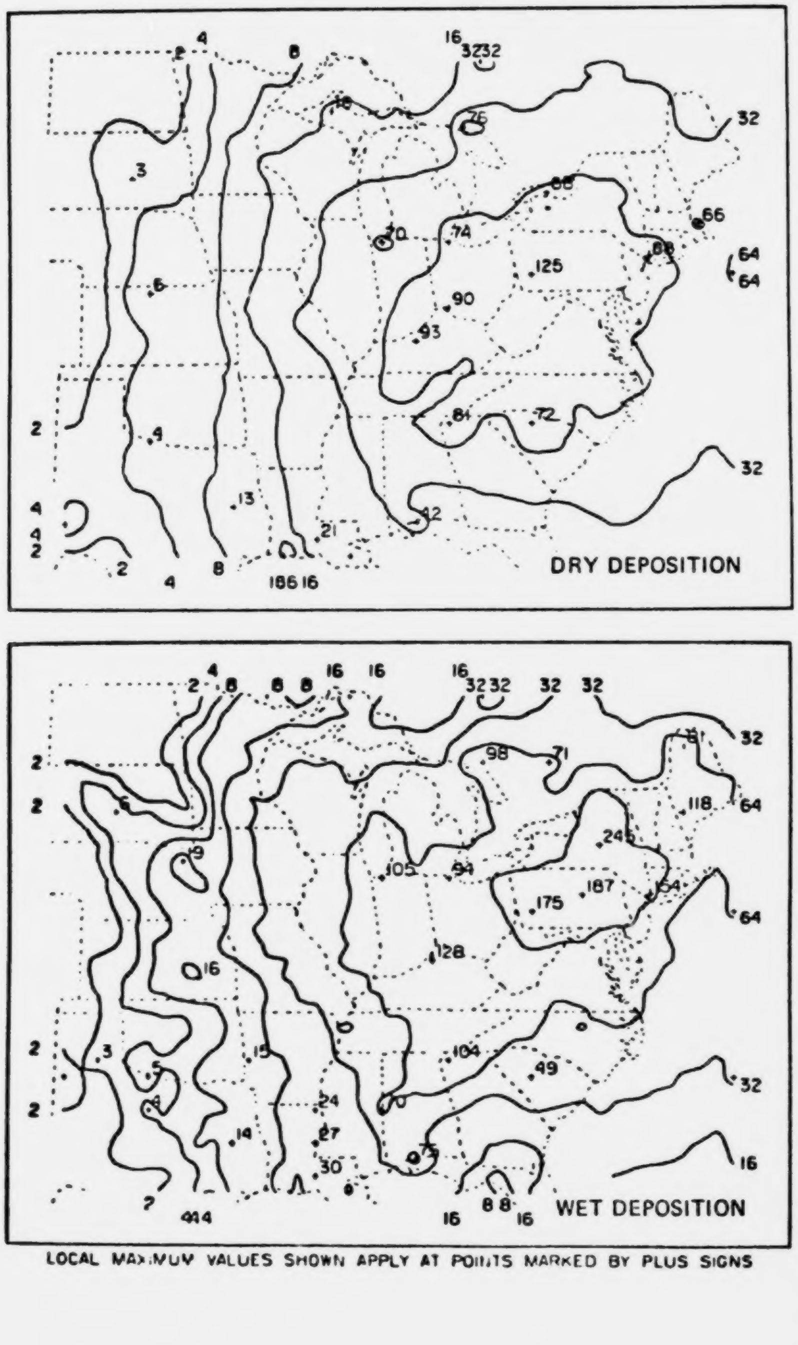
LOCAL MAXIMUM VALUES SHOWN APPLY AT POINTS MARKED BY PLUS SIGNS

Figure A5-13 Calculated annual dry and wet depositions of SO_2 (10 mg/m^2) for 1977 from ENAMAP-1


DRY DEPOSITION
4
16
64
64
64
64
256
256
64
4
16
4
4
4
4
16
64
64
16
87
95
216
47
2153
389
250
442
289
302
1012704
686
547
707731
593
147
1411
1708585
948
1364
2970
1052
946
1713
879
346
523
1047
1870
824
327
817
122
821
568
597
87
273
913
1229
567
412
458
705
469
258
1149
290333
WET DEPOSITION
4
16
16
16
16
16
64
64
64
40
110
12
1328
101
131
273
188
251
3
280
541
408517
1
405
462
1095176
105
707
1031
1288
880
1188
2314
859
585
227
537
1199
272
671
772
750
317
332
821
64
507
290
237311
46
163
588
989
23
161
190
198
661
226
244
98
41
403390
1173
53
16
16
16
4
4
4
16
64
64
64

LOCAL MAXIMUM VALUES SHOWN APPLY AT POINTS MARKED BY PLUS SIGNS

Figure A5-14 Calculated annual dry and wet depositions of SO_4 (10 mg/m^2) for 1977 from ENAMAP-1


DRY DEPOSITION
4
8
16
3232
32
3
76
88
66
70
74
125
88
64
64
6
90
93
2
4
81
72
32
4
4
2
13
21
42
2
4
8
16516
WET DEPOSITION
2
4
8
8
8
16
16
16
3232
32
32
32
2
98
71
81
2
6
118
64
9
246
105
94
187
175
164
64
16
128
2
3
15
104
49
32
2
5
24
27
14
30
16
16
88
16
2
444

LOCAL MAXIMUM VALUES SHOWN APPLY AT POINTS MARKED BY PLUS SIGNS

Model: AES-LRT

Modeling Group: Atmospheric Environment Service, Marvin Olson and Eva Voldner

Model Type: Lagrangian

Emission Data: 127 km 127 km - polar stereographic CMC* grid

Wind Data: upper air observations, objectively** analyzed at 6 hourly intervals at 4 levels on 381 x 381 km CMC grid (1978)

Precipitation Data: 24 hour amount, objectively analyzed on 127 x 127 km CMC grid

Mixing Height: climatological (Portelli, Holzworth) as a function of month averaged onto 127 x 127 km CMC grid (mean daily = (morn. min. + aft. max.) /2)

Chemistry: first order SO_2/SO_4

Dispersion: - instantaneously in a grid box (127 x 127 km)
- individual trajectories (96-hour backward)

Removal Processes: wet and dry deposition of SO_2 and SO_4

Model Outputs: (1) concentration and deposition fields for SO_2, SO_4
(2) source receptor matrix (11 x 9)

Resolution: 1 month, 127 km square.

Area of Application: Eastern North America

---

* Canadian Meteorological Centre

** 3-D data assimilation scheme that incorporated hydrostatic and height-wind balance routines

Parameter Values: SO_2/SO_4 = 1%/hour

$VDSO_2$ = 0.5 cm/sec.

$VDSO_4$ = 0.1 cm/sec.

Scavenging ratio: SO_2 = 30,000 ($.3 \times 10^5$)

SO_4 = 850,000 (8.5×10^5)

Descriptive Material:

Wet deposition is parameterized by using the scavenging ratio approach and the 24-hour precipitation amount.

Dry deposition is parameterized through the use of fixed deposition velocities.

Trajectories are calculated using winds interpolated to the 925 mb level and using computed vertical motions.

Comparisons with Data:

Preliminary results indicate some overprediction of sulfur dioxide concentrations and some underprediction of wet deposition, but generally the overall concentration patterns and episode occurrences agree quite well with measurements (correlations between 0.4 and 0.9).

Figures A5-15 through A5-18 compare daily average measured and computed concentrations and ratios of computed to measured monthly concentrations.

Figure A5-15 AES-LRT computed and measured daily mean SO_2 concentrations during October 1977 at Albany, N.Y. (measured-solid, computed-dashed)

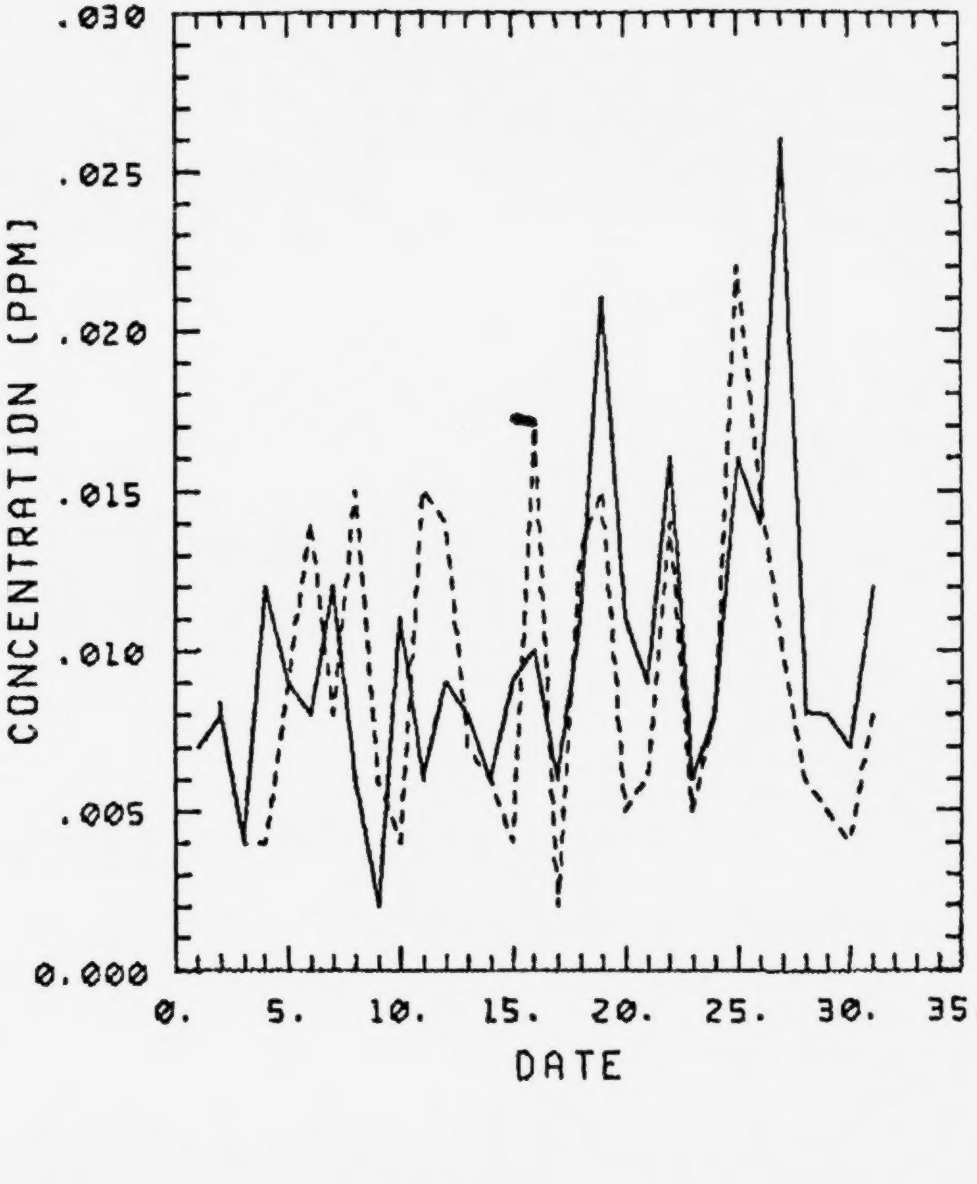


Figure A5-16 AES-LRT computed and measured daily mean sulfate concentrations during October 1977 at Port Huron, Mich. (measured-solid, computed-dashed)

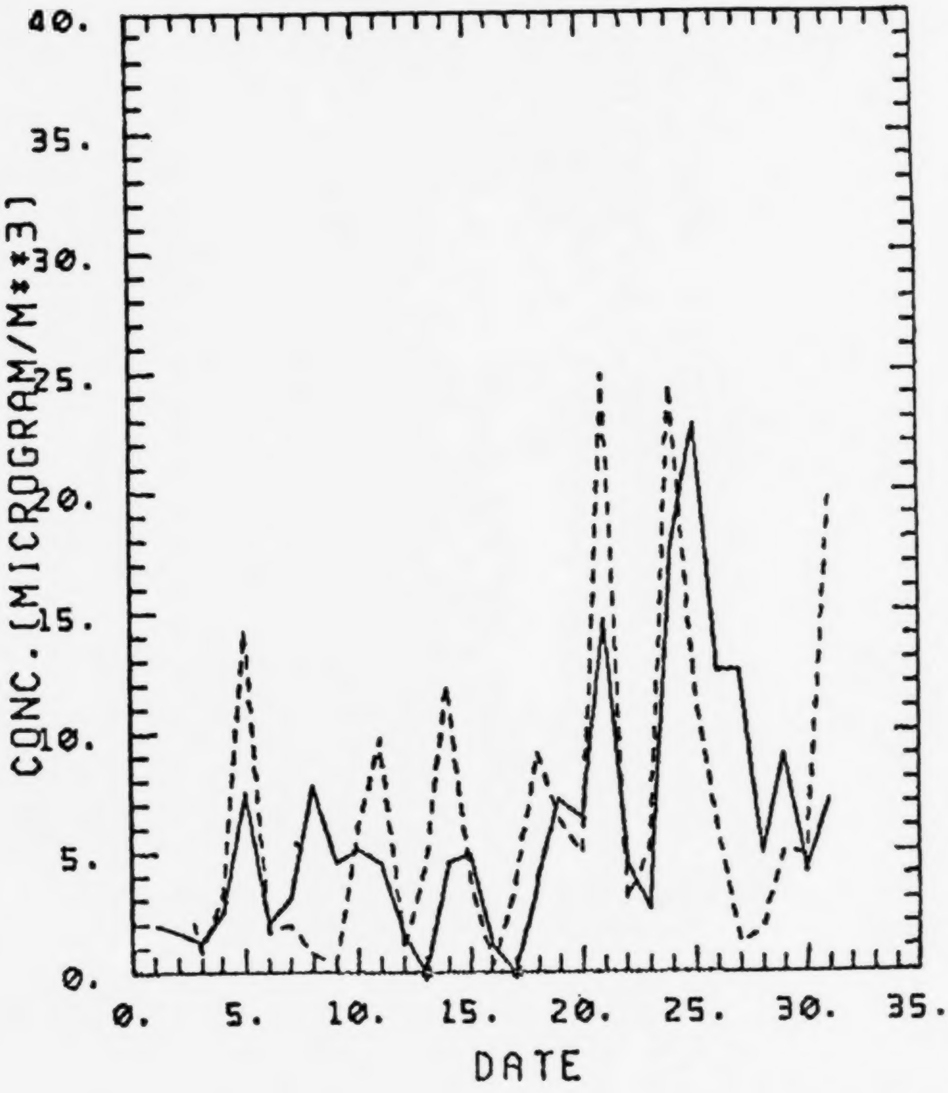


Figure A5-17 Ratios of AES-LRT computed to measured monthly precipitation weighted sulfate concentrations in the rain and percent contribution from direct sulfate scavenging (in parentheses) for October 1977.

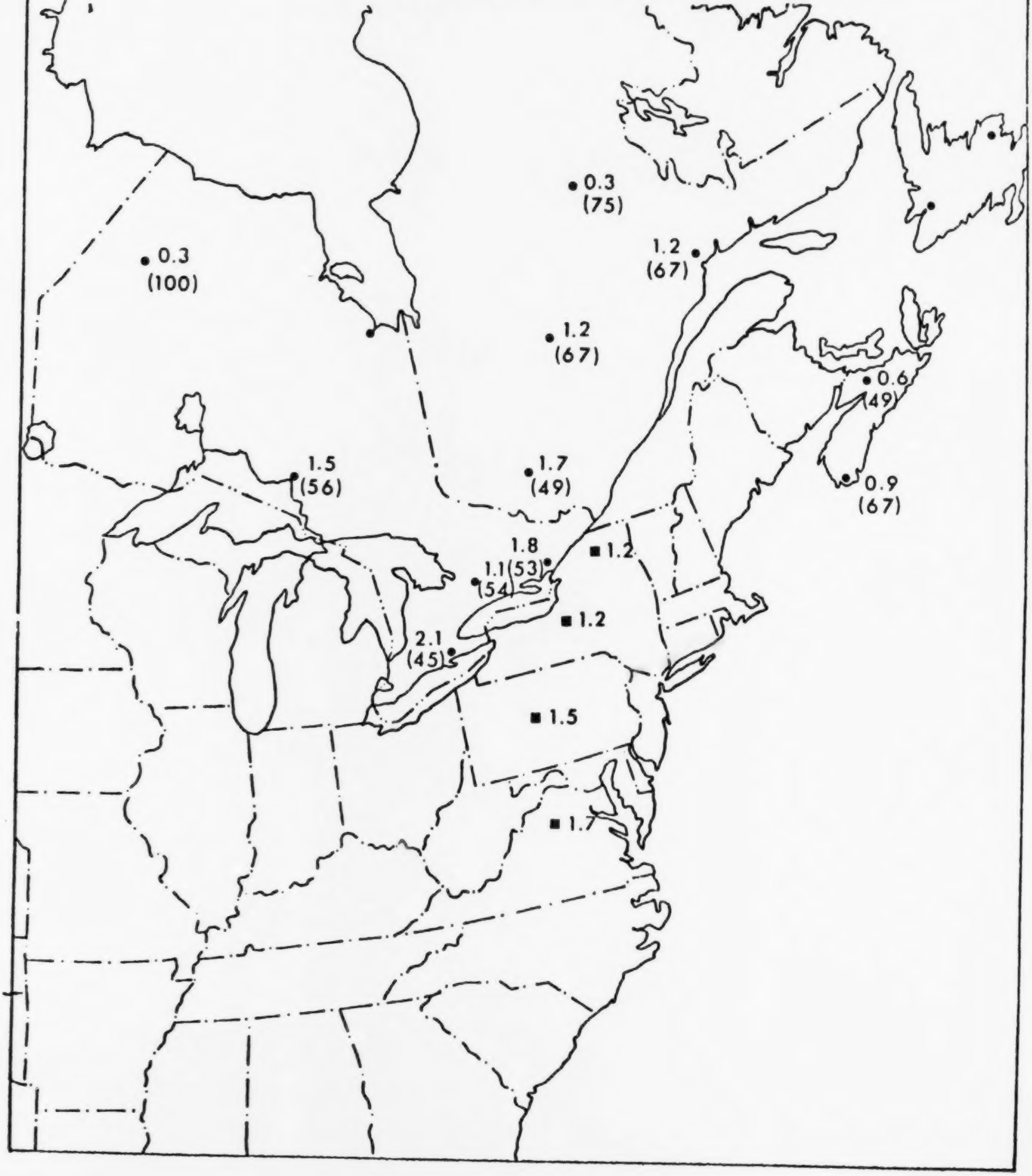
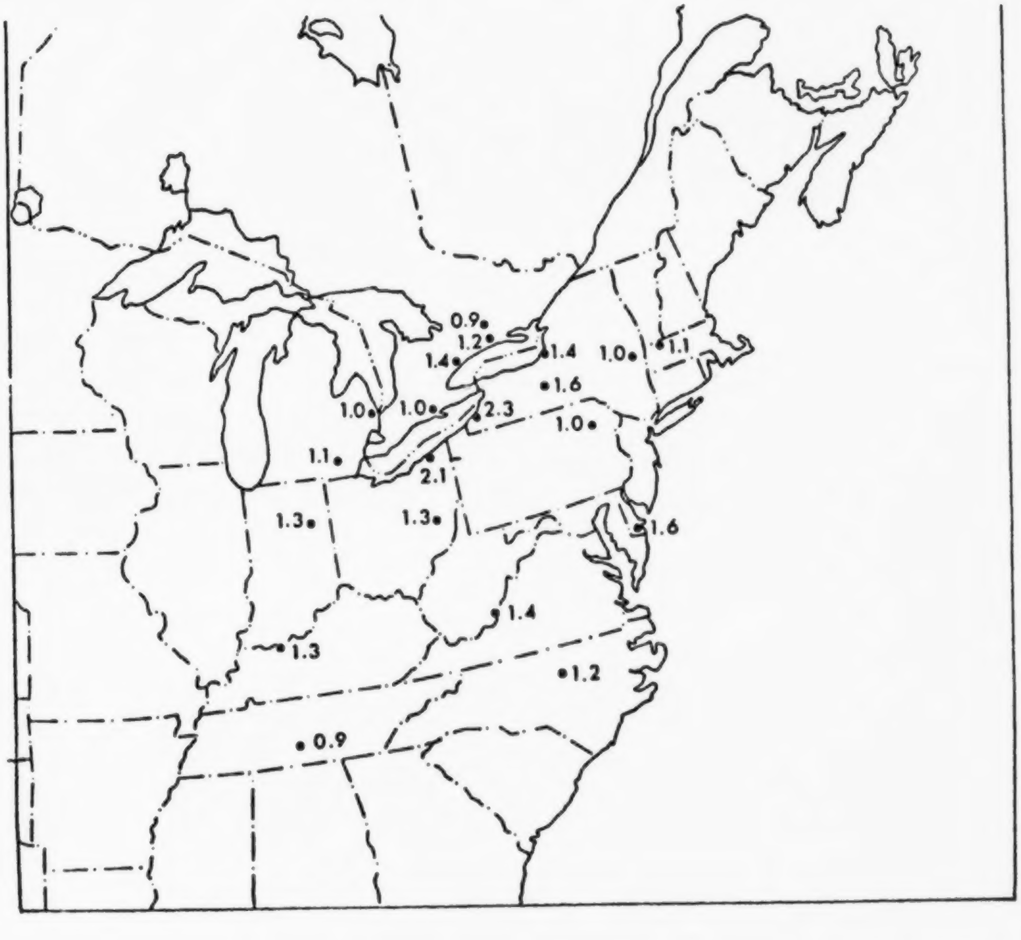

0.3
(75)
0.3
(100)
1.2
(67)
1.2
(67)
0.6
(49)
1.5
(56)
1.7
(49)
0.9
(67)
1.8
1.1
(53)
(54)
1.2
1.2
2.1
(45)
1.5
1.7

Figure A5-18 Ratios of AES-LRT computed to measured monthly mean sulfate concentrations in the air for October 1977


0.9
1.2
1.4
1.4
1.0
1.1
1.6
1.0
1.0
2.3
1.0
1.1
2.1
1.3
1.3
1.6
1.4
1.3
1.2
0.9

Model: OME-LRT

Modeling Group: Ontario Ministry of the Environment,
Akula Venkatram

Model Type: Statistical Trajectory

Emission Data:
- point source: a function of height
- area sources: in the form of effective point source at emission weighted geometric mean co-ordinates.

Wind Data: statistics of σ_u and σ_v from Tennekes (long term average only)

Precipitation Data: duration and frequency of wet and dry periods (Slinn, 1979)

Mixing Height: constant value of 1000 metres

Chemistry: first order SO_2/SO_4

Dispersion:
- instantaneous mixing
- solution of the Lagrangian dispersion equation
- function of trajectory spread

Removal Processes: Stochastic scavenging - wet and dry removal of SO_2 & SO_4

Model Outputs:
(1) concentration and deposition fields for SO_2 & SO_4
(2) source receptor matrix (11 regions)

Resolution: Annual, 100 km.

Area of Application: North America

Parameter Values: $\sigma_x = U_m T$

$\sigma_y = V_m T$

where $U_m = 10$ m/s

$V_m = 6$ m/s

$SO_2/SO_4 = 1\%$/hour (dry & wet)

Effective washout rate for $SO_2 = 3 \times 10^{-5}$ 1/sec.

Precipitation scavenging of $SO_4 = 1 \times 10^{-4}$ 1/sec.

$VDSO_2 = 0.5$ cm/s

$VDSO_4 = 0.05$ cm/s

$T_d = 46$ hours - Langrangian dry period

$T_w = 7$ hours - Lagrangian wet period

$\overline{L} = 1000$ m

$\overline{U} = 10$ m/s

Ratio of SO_2 to SO_4 at the Source = 0.98/0.02

Descriptive Material:

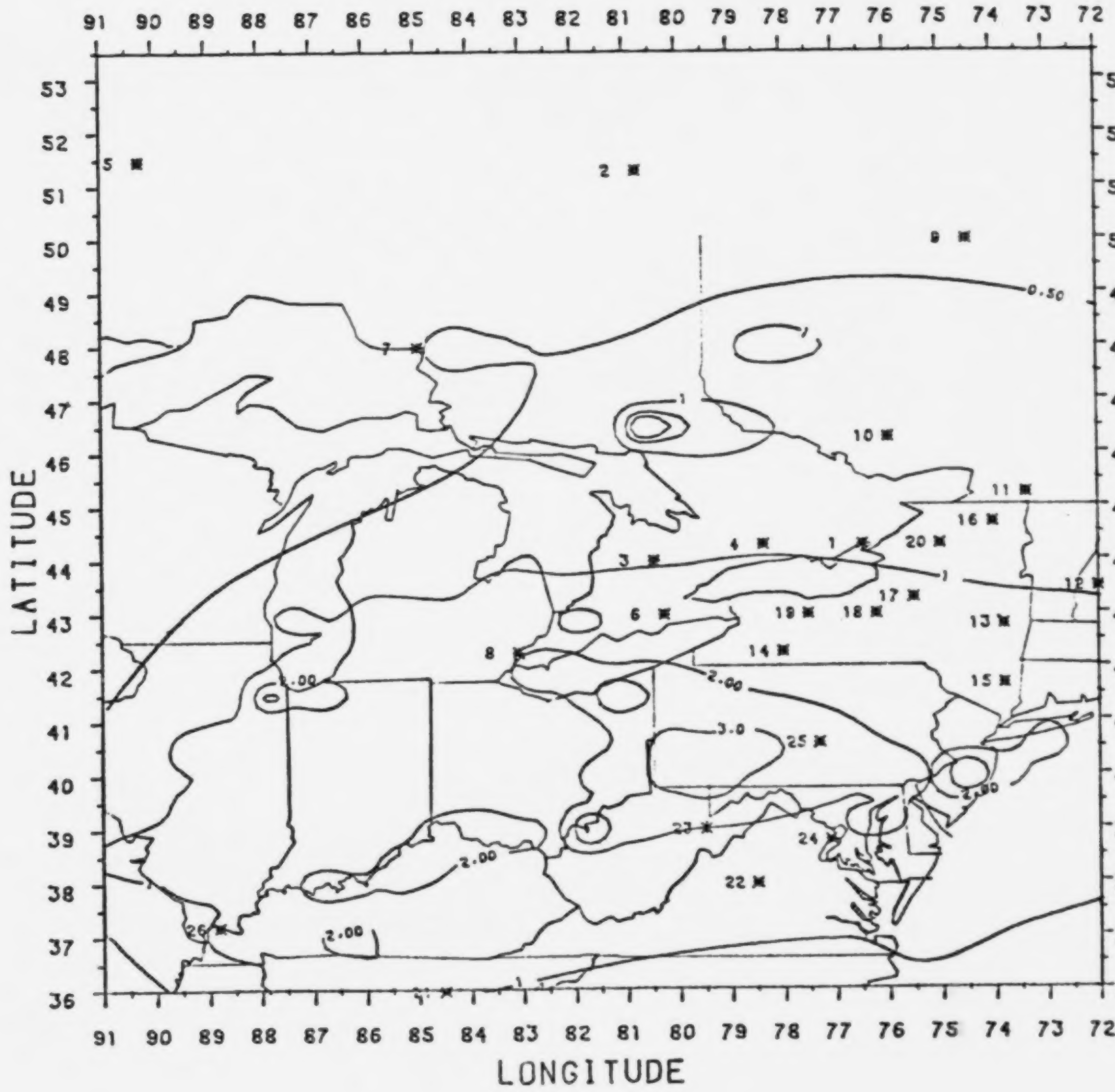
The horizontal dispersion of pollutants is based on a Gaussian puff whose mean motion follows that of large scale synoptic flows. The standard deviations of the Gaussian puff are related to the statistics of trajectories from the source of interest. Scavenging of pollutants is treated with a stochastic model which accounts for the distinctly different probabilities of rain in synoptically dry and wet regions. The model also allows for different SO_2 to SO_4 conversion rates in wet and dry periods. The statistical LRT model is a "convolution" of the dispersion and scavenging sub-models.

Comparisons with Data:

Figure A5-19 shows modeled total wet deposition of sulphur for 1977.

Table A5-1 details the verification data and correlation coefficients for various agglomerations of sources from the OME-LRT Model.

Figure A5-19 OME-LRT model predictions of annual wet deposition of sulfur in gm/m^2/year. Stars in figure correspond to monitors in the CANSAP and U.S. networks. Numbers next to stars are station codes referred to in Table A5-1


91
90
89
88
87
86
85
84
83
82
81
80
79
78
77
76
75
74
73
72
53
52
51
50
49
48
47
46
45
44
43
42
41
40
39
38
37
36
LATITUDE
LONGITUDE
0.50
1
2.00
3.0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
22
23
24
25
26

Station No	Receptor Name	Wet sulfur deposition OBS $(g/m^2/yr)$	 PRED	 OBS/PRED
1	Kingston, Ont	1.26	0.93	1.35
2	Moosonee, Ont	0.58	0.33	1.76
3	Mount Forest, Ont	2.32	0.96	2.42
4	Peterbough, Ont	1.81	0.94	1.93
5	Pickel Lake, Ont	0.39	0.28	1.39
6	Simcoe, Ont	2.34	1.49	1.57
7	Wawa, Ont	0.91	0.52	1.75
8	Windsor, Ont	2.98	2.00	1.49
9	Chibougamau, Que	1.06	0.42	2.52
10	Maniwaki, Que	0.71	0.75	0.95
11	Montreal, Que	2.35	0.88	2.67
12	Merrimach Cnty, N.Y.	0.91	0.93	0.98
13	Albany Cnty, N.Y.	1.20	1.21	0.99
14	Allegany Cnty, N.Y.	2.20	1.58	1.39
15	Dutchess Cnty, N.Y.	1.20	1.48	0.81
16	Essex Cnty, N.Y.	0.84	0.84	1.00
17	Oneida Cnty, N.Y.	1.70	1.08	1.57
18	Onondaga Cnty, N.Y.	0.79	1.19	0.66
19	Ontario Cnty, N.Y.	1.20	1.34	0.90
20	St. Law. Cnty, N.Y.	1.00	0.89	1.12
21	Oak Ridge, Tenn	1.30	1.04	1.25
22	Charlottesville Vir	0.91	1.31	0.69
23	Tucker Cnty, W.V.	2.00	1.94	1.03
24	Washington, D.C.	1.00	1.83	0.55
25	Lewistown, Penn	0.98	2.21	0.44
26	Paducah, Kentucky	0.57	1.29	0.44

LINEAR ANALYSIS: OBSERVED DEPOSITION = a + b* PREDICTED DEPOSITION

Receptor Location	r^2	$a(g/m^2/yr)$	b	Receptor Excluded
Canada	0.76	0.24	1.49	
Canada	0.84	0.16	1.48	11
U.S.	0.09	0.73	0.34	
U.S.	0.47	0.05	0.98	24, 25, 26
All PT	0.19	0.67	0.58	
All PT	0.51	0.24	1.04	11, 24, 25, 26
All PT Can Obs Reduced 30%	0.70	0.12	0.97	11, 24, 25, 26

Table A5-1 Comparison of OME-LRT model predictions with observations of wet deposition of sulfur for 1977 (Galloway and Whelpdale, 1980).

Model: RCDM (Regional Climatological Dispersion Model)
Fay and Rosenzweig

Modeling Group: Teknekron Research Inc., Brand Niemann and Carl Benkeley

Model Type: Analytical Eulerian

Emission Data:
- single or multiple point and area sources
- SURE inventory

Wind Data: - resultant average vector wind field

Precipitation Data: seasonal, regional average

Mixing Height: use seasonal value at receptor point

Chemistry: slow and irreversible (eg. SO_2/SO_4) or fast and reversible (e.g. NO/NO_2)
- linear decay or equilibrium mass coefficient

Dispersion:
- steady state diffusion equation (two-dimensional)
- regional scale diffusivity

Removal Processes:
- uniform in space
- wet and dry
- first order rate constant

Model Outputs:
(1) Long term average pollutant concentrations and deposition patterns
(2) Gridded field
(3) Transfer matrix (arbitrary number of areas)

Resolution: >50 km from sources, regional scale.

Area of Application: Eastern North America

Parameter Values: $\bar{L}$ = 1000 m

$\bar{u}$ = 3.2 m/s

θ = 265° True

VD_{SO_2} = .01 m/s

Tw = 3×10^5 seconds

= net depletion time = 10^5 seconds

D_H = Diffusivity = 6.4×10^5 m^2/sec.

Descriptive Material:

Fay and Rosenzweig assumed that the longer period sulfur dioxide and sulfate concentrations from a point source can be described by the 2-dimensional steady state advection-diffusion equation in which the horizontal eddy diffusivity and conversion and removal rates are uniform in space.

The RCDM is an appropriate compromise between the original Fay and Rosenzweig application which used only one wind speed and direction for the entire eastern U.S. and the NOAA/ARL and ASTRAP models which use the highest temporal and spatial resolution available in upper air data.

The compromise decided upon was to use the seasonal and annual resultant wind vectors at all the upper air stations in the eastern U.S. and southeastern Canada.

Comparisons with Data:

Fay and Rosenzweig found generally good agreement between sulfur dioxide predictions from their analytical model and numerical predictions from the NOAA/ATDL trajectory model.

The sulfate predictions from the steady state model are in general agreement with those from the ASTRAP model which uses high resolution meteorological data to compute an ensemble average of trajectory statistics.

Sensitivity analysis of the RCDM show in general that SO_2 concentrations are most sensitive to the mixing height and the inverse total depletion rate while the sulfate concentrations are most sensitive to mixing height and the inverse chemical conversion rate. The RCDM has been evaluated against historical sulfate data and current sulfur dioxide and sulfate data. The RCDM predictions were found to be in generally good agreement with regional sulfate concentrations during 1960-1974 and with current sulfur dioxide and sulfate concentrations. Both the historical and current regional sulfate concentrations show a regional pattern of elevated sulfate concentrations which are roughly symmetrical about the 11 contiguous states with the highest sulfur dioxide emissions.

The RCDM also gives generally good agreement with winter and summer season regional sulfur dioxide and sulfate concentrations when the seasonal mixing heights from climatological data are used and the inverse chemical conversion rate (i.e., SO_2 residence time) is decreased slightly for the summer and increased slightly for the winter over the annual value.

The predicted wet sulfur deposition values are in general agreement with those computed from the MAP3S and EPRI precipitation chemistry networks in the region of highest SO_2 emissions. However, the RCDM does not predict the observed maxima in wet sulfur deposition in regions like southeastern Canada beyond the region of highest SO_2 emissions in the eastern U.S.

Figures A5-20 through A5-26 illustrate the verification data available for this model.

Figure A5-20 Isopleths of annual SO_2 concentrations (ug/m^3) simulated by the RCDM

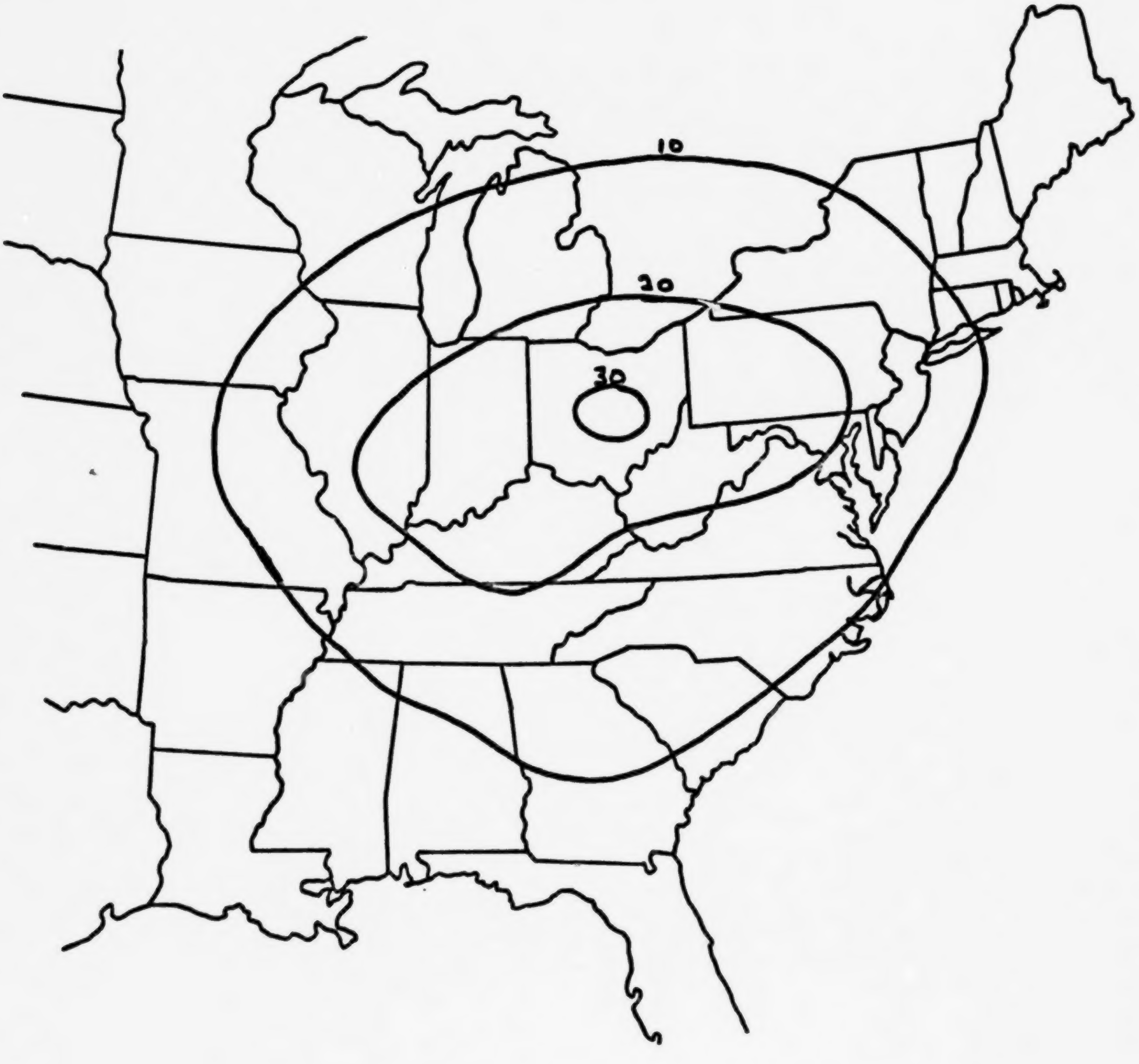


Figure A5-21 Isopleths of annual sulfate concentrations ($\mu g/m^3$) simulated by the RCDM

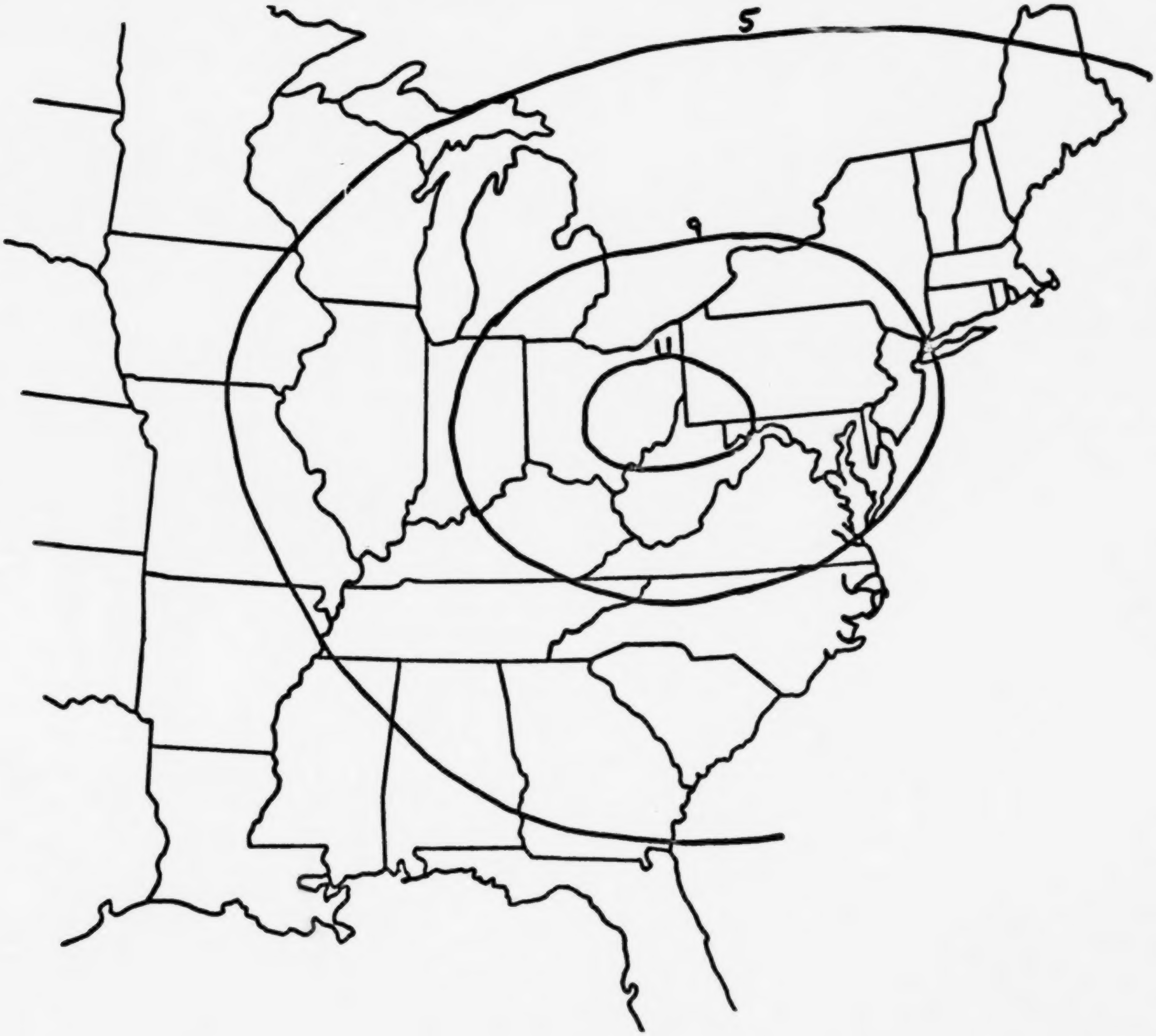


Figure A5-22 Three-year average (1975-1977) of AQCR average sulfate concentrations (ug/m^3)

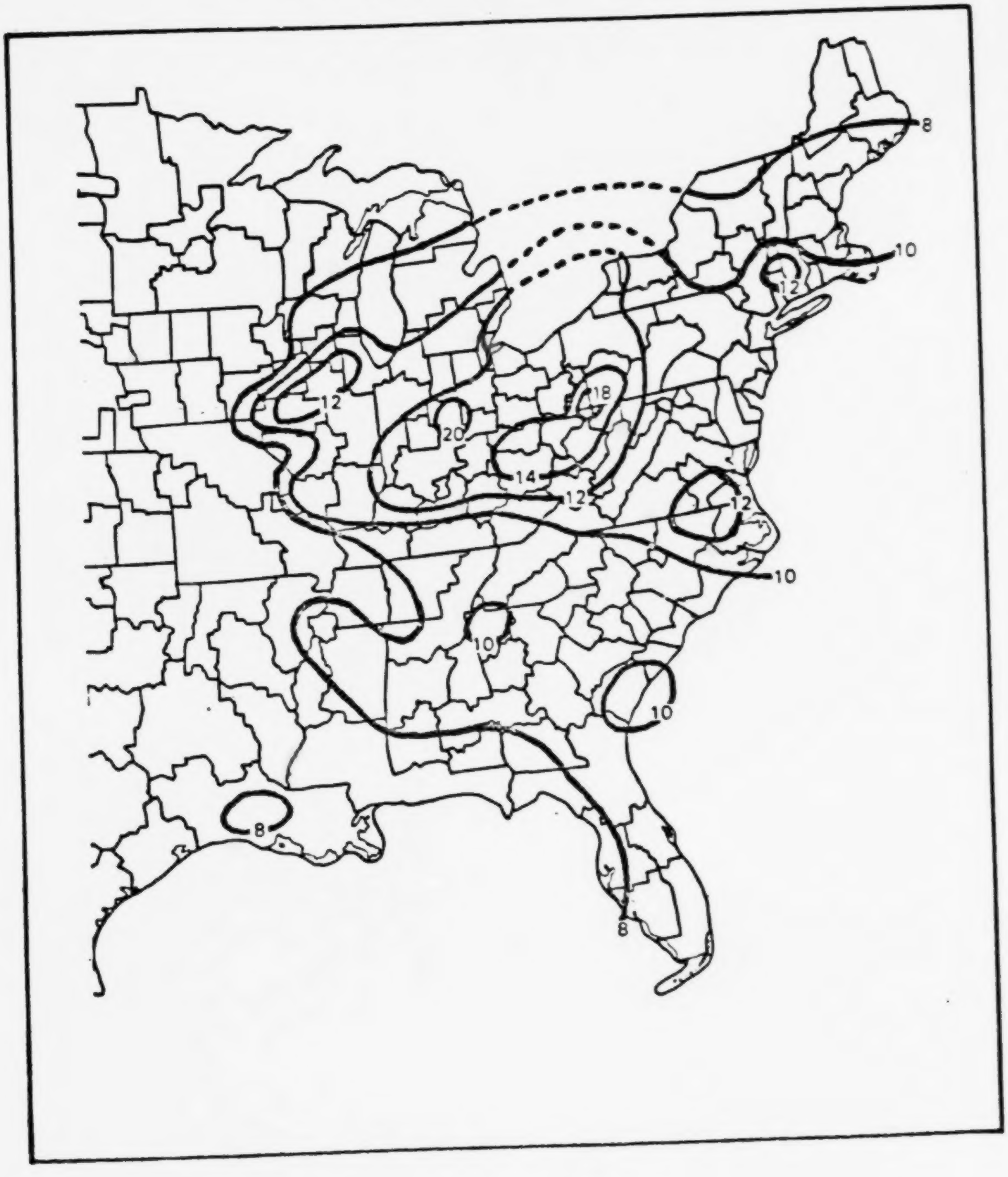

8
10
12
12
18
20
14
12
12
10
10
10
8
8

Figure A5-23 Annual average sulfate concentrations ($\mu g/m^3$) at Ontario Hydro monitors in 1978

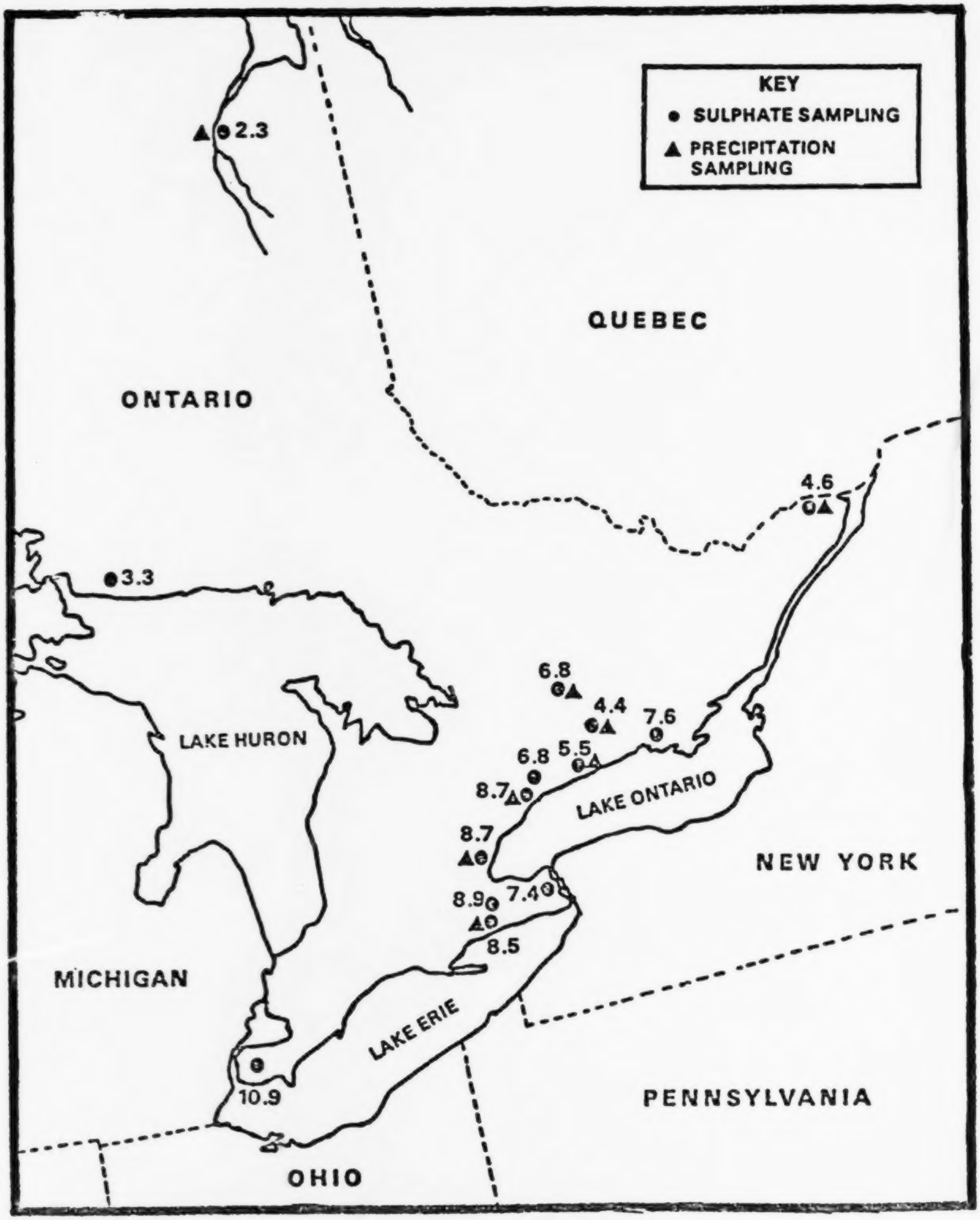

KEY
● SULPHATE SAMPLING
▲ PRECIPITATION SAMPLING
2.3
QUEBEC
ONTARIO
4.6
3.3
6.8
4.4
7.6
LAKE HURON
6.8
5.5
8.7
LAKE ONTARIO
8.7
NEW YORK
8.9
7.4
8.5
MICHIGAN
LAKE ERIE
10.9
PENNSYLVANIA
OHIO

Figure A5-24 "Annual average" sulfate concentrations ($\mu g/m^3$) at the SURE monitors

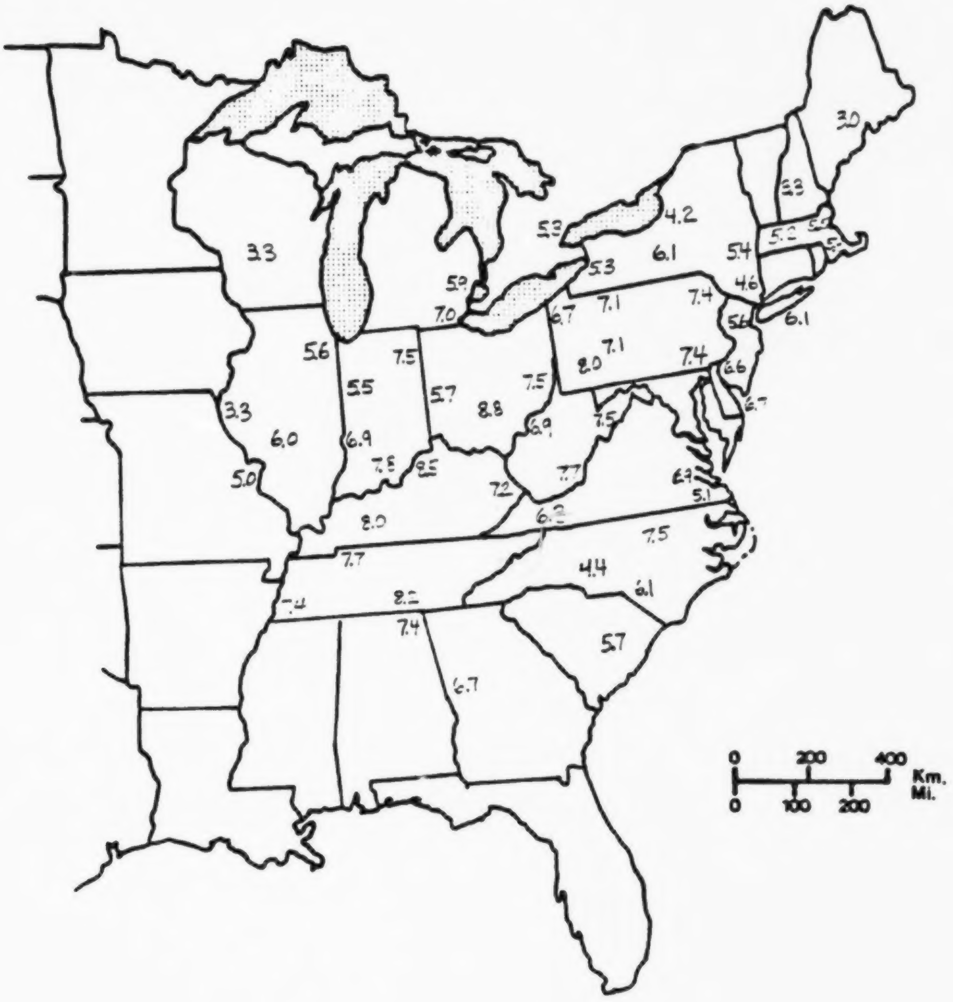

3.0
3.3
4.2
5.3
5.2
5.5
3.3
6.1
5.4
5.9
5.3
4.6
7.0
6.7
7.1
7.4
5.6
6.1
5.6
7.5
7.1
8.0
7.4
7.5
6.6
5.5
5.7
8.8
3.3
6.7
6.9
6.0
6.9
7.5
7.8
8.5
7.7
5.0
7.2
6.9
5.1
8.0
6.2
7.5
7.7
4.4
6.1
7.4
8.2
7.4
5.7
6.7
0
200
400
Km.
Mi.
0
100
200

Figure A5-25 Isopleths of wet sulfur deposition (g/m^2yr) simulated by the RCDM

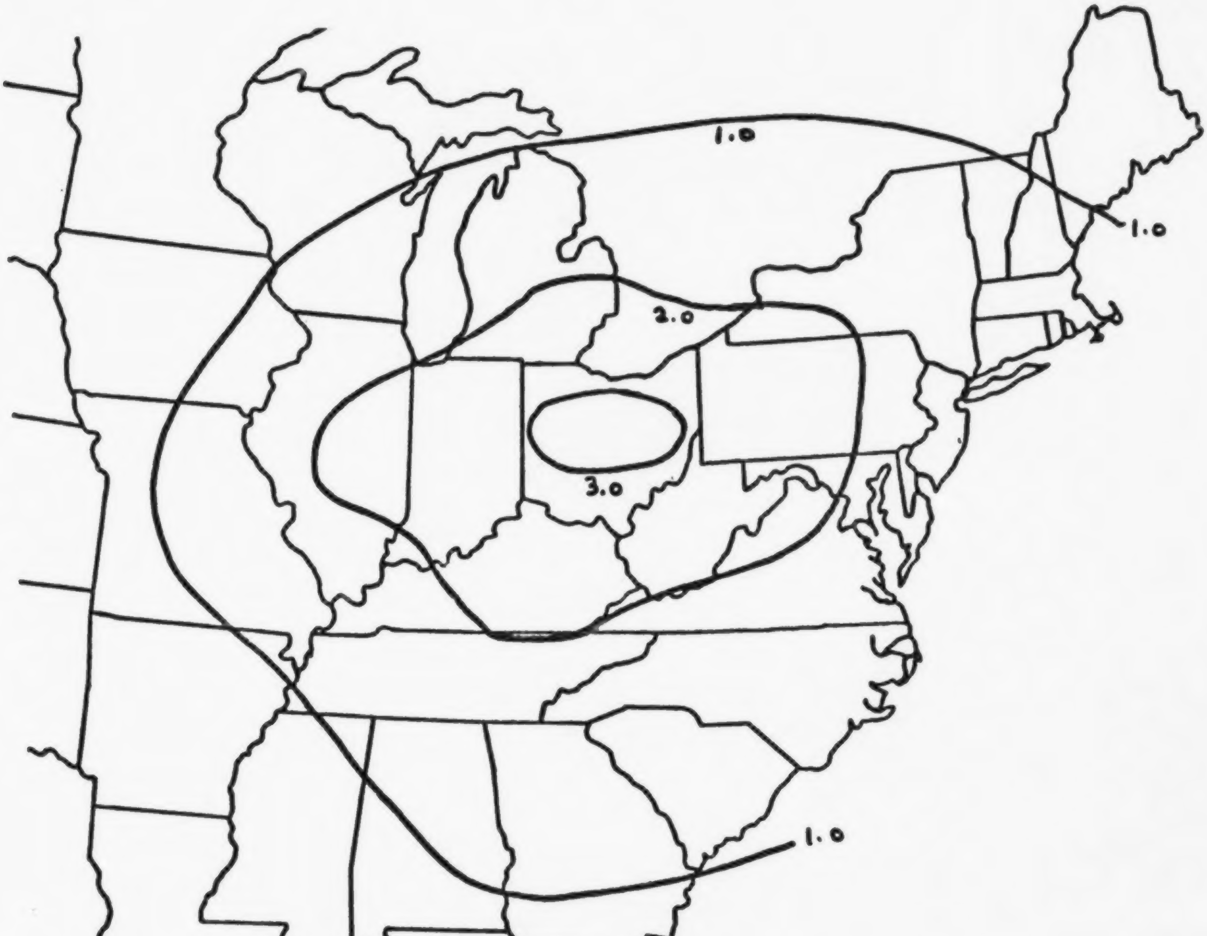
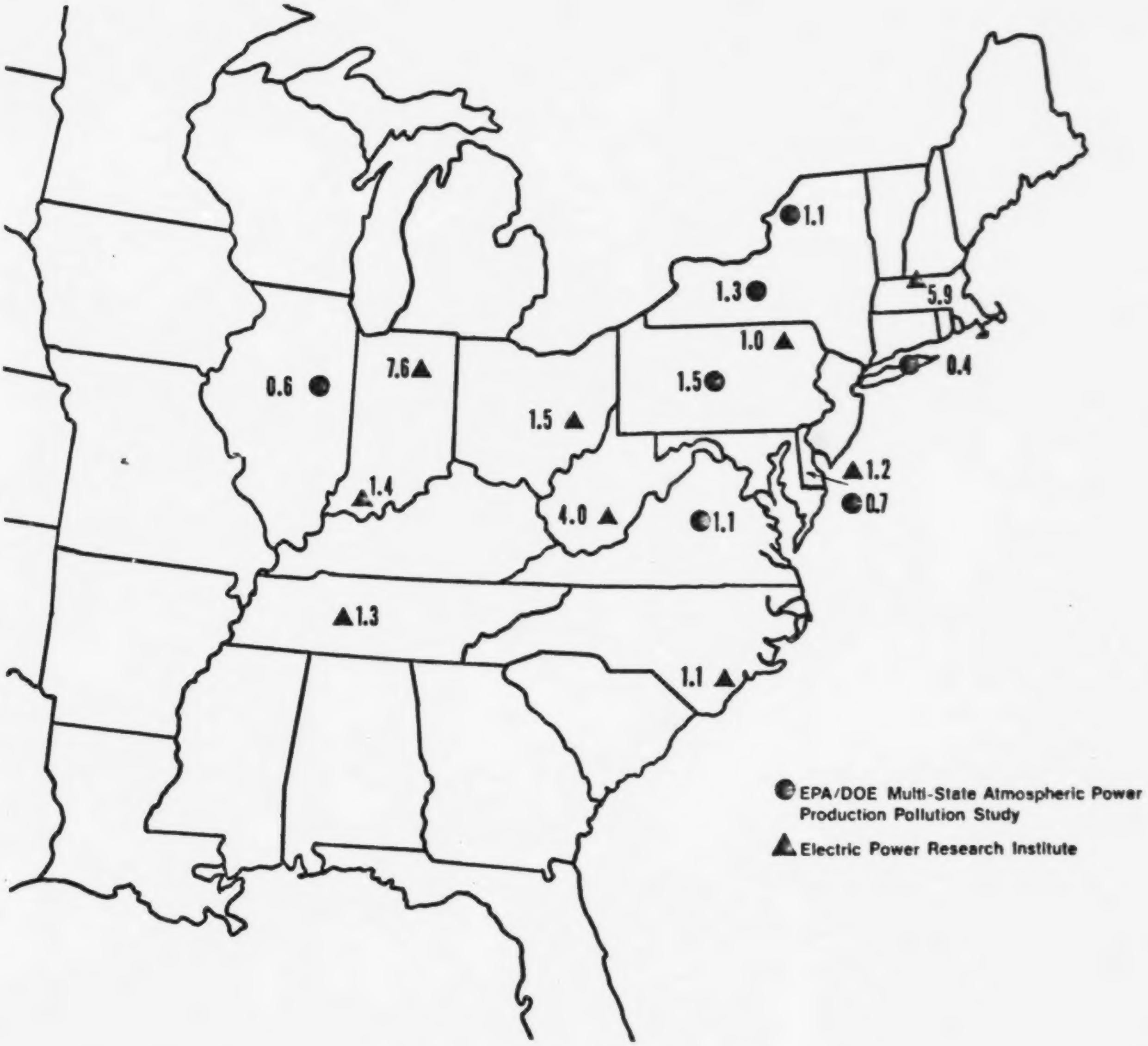

1.0
1.0
2.0
3.0
1.0

Figure A5-26 Wet sulfur deposition (g/m^2yr) at event monitoring sites in the northeastern U.S. (1976-1979)


● 1.1
1.3 ●
▲ 5.9
1.0 ▲
● 0.4
0.6 ●
7.6 ▲
1.5 ●
1.5 ▲
▲ 1.2
● 0.7
▲ 1.4
4.0 ▲
● 1.1
▲ 1.3
1.1 ▲
● EPA/DOE Multi-State Atmospheric Power Production Pollution Study
▲ Electric Power Research Institute

Appendix 6

Source Region and Inventory Description

NOTE: An addendum to this appendix containing more detailed information has been produced and will be updated periodically.

LIST OF FIGURES AND TABLES

PAGE

TABLE A6-1 Comparison of State Emissions Totals and Aggregate - Grid Totals (based on SURE Phase II Inventory) A.6-2

TABLE A6-2 SURE II SO_2 Emissions Allocated to Grid Aggregate Areas. A.6-4 A.6-5

TABLE A6-3 SURE II SO_2 Emissions Allocated to Grid Aggregate Areas Subdivided by by Stack Height A.6-6, A.6-7

FIGURE A6-1 SO_2 Emission Rate with Height (SURE II Inventory) A.6-8

TABLE A6-4 Principal Reason for Selection of Sensitive Areas A.6-9

TABLE A6-5 Relationship Between Area Numbers and Abbreviations on Large Map A.6-10

TABLE A6-6 Relationship Between Canadian Regions and the 63 Aggregated SURE Grid Areas A.6-11

TABLE A6-7 Relationship Between Canadian Receptor Areas and ARMS Sensitive Areas A.6-12

A6.1 A Description of the SURE II Extended Grid: Source Regions and Sensitive Receptor Areas

The 80km grid cells in the Sulfate Regional Experiment (SURE) Phase II emission inventory have been aggregated to define 63 distinct areas. These 63 areas have been selected to include logical source regions or sensitive receptor areas. Each entire SURE II grid cell (undivided) has been assigned to one of the 63 areas with attention being paid to matching state emission totals and state boundaries as closely as possible.

TABLE A6-1 Comparison of State Emissions Totals and Aggregate - Grid Totals (based on SURE Phase II Inventory)

State	Emissions (1000s tons/year) SURE Data Files	Aggregate of Grid Squares	Difference (Grid Aggregate - Data Base) 1000 tons/year	Difference (Grid Aggregate - Data Base) Percent
Alabama	1290	1209	-81	-6
Arkansas	79	90	+11	+14
Connecticut	66	45	-21	-32
Delaware	129	131	+2	+2
Florida	1788	1798	+10	+1
Georgia	916*	942*	+26	+3
Illinois	2344	1994	-350	-15
Indiana	2189	2545	+356	+16
Iowa	535	557	+22	+4
Kentucky	1824	1809	-15	-1
Louisiana	636	614	-22	-3
Maine	337	339	+2	+1
Maryland & D.C.	352	455	+103	+29
Massachusetts	666	670	+4	+1
Michigan	2292	2627	+355	+13
Minnesota	521	508	-13	-2
Mississippi	447	501	+54	+12
Missouri	1288	1291	+3	0
New Hampshire	169	173	+4	+8
New Jersey	555	692	+137	+25
New York	974	698	-276	-28
N. Carolina	984*	1004*	+20	+2
Ohio	4533	4759	+226	+5
Pennsylvania	2480	2150	-330	-15
Rhode Island	43	33	-10	-23
S. Carolina	459	429	-30	-7
Tennessee	1332*	1360*	+28	+2
Vermont	7	6	-1	-14
Virginia	695	644	-51	-7
West Virginia	1349	1355	+6	0
Wisconsin	937	935	-2	0
Ontario (part)	2228	2088	-140	-6
Quebec (part)	1017	1020	+3	0
	35509	35519	+10	0.03%

---

* Emissions in S. Appalachain sensititve area excluded

The SURE-II Extended Grid

The grid has an 80-km mesh, with 41 cells east-west and 42 north-south; because it is an extension of an earlier version, the cells are numbered 0 to 40 and -9 to 32 in the X and Y, or east and north, directions respectively.

If the 0 to 30 E-W index is denoted I, and the -9 to 32 N-S index denoted J, the one-dimensional index used is IDX = I+ 41 * (J-1).

The grid is "centered" around 81^{0} west longitude, 39^{0} 38' latitude, which corresponds to x=500.0km, and y=4407.02 km in the transverse mercator (TM) system used for the grid. This corresponds to the following TM coordinates for the grid lines:

42 N-S lines at -780, -700,..............,+2420, +2500 km

43 E-W lines at 2687.02, 2767.02,.............. 5967.02, 6047.02 km

TABLE A6-2 SURE II SO_2 Emissions Allocated to Grid Aggregate Areas.

Area	SO_2 Emissions 1000s tons per year	AREA CENTROID		EMISSION CENTROID	
		X	Y	X	Y
1. Maine	332.0	27.36	20.79	26.92	19.45
2. New Hampshire SA*	41.7	25.50	20.00	25.16	19.40
3. Vermont	5.8	24.00	18.50	24.00	18.29
4. Southern New Hampshire	138.4	24.67	17.33	24.90	17.28
5. Massachusetts	670.1	25.67	16.00	25.80	15.98
6. Rhode Island	33.2	25.00	15.00	25.00	15.00
7. Connecticut	45.1	24.00	15.00	24.00	15.00
8. Adirondack SA*	12.0	22.50	18.50	22.75	18.54
9. Western New York	307.1	18.20	16.40	18.54	16.88
10. Southeastern New York	378.9	21.46	16.69	21.83	16.08
11. New Jersey	691.7	23.00	13.00	22.85	13.64
12. Southeastern Pennsylvania	569.0	21.67	13.33	21.83	13.35
13. Central Pennsylvania	476.9	19.88	14.13	20.00	13.46
14. Western Pennsylvania	1075.8	17.40	14.20	17.09	13.42
15. Pennsylvania SA*	55.2	18.00	12.50	18.00	12.51
16. Maryland & DC	428.2	20.17	11.00	19.98	11.11
17. Delaware	130.5	21.67	11.00	21.34	11.66
18. Virginia	643.8	18.35	9.06	19.13	8.91
19. Northeastern West Virginia	1086.3	16.67	11.67	16.26	11.89
20. Southwestern West Virginia	268.3	15.17	10.00	15.01	10.11
21. Eastern Kentucky	753.9	11.58	9.17	10.58	9.87
22. Western Kentucky	1054.6	8.00	9.00	8.11	9.00
23. Western Tennessee	726.2	6.89	6.78	7.52	7.17
24. Eastern Tennessee	633.2	10.80	7.00	11.32	7.42
25. Southern Appalachain SA*	72.8	12.83	6.00	13.14	6.35
26. Central North Carolina	512.4	15.20	6.80	15.34	7.12
27. Eastern North Carolina	473.2	18.94	5.94	18.20	6.25
28. South Carolina	423.0	16.07	3.86	15.97	3.96
29. Northwestern Georgia	620.8	11.40	3.80	11.08	4.40
30. Southeastern Georgia	321.4	13.21	1.42	13.66	1.74
31. Southern Florida	647.7	15.33	-5.89	14.75	-4.59
32. Northern Florida	179.8	15.17	-2.33	14.81	-2.57
33. Florida SA*	59.6	13.50	-1.50	13.61	-1.52
34. Western Florida	911.8	9.80	-0.90	8.38	-0.31
35. Alabama	1208.5	8.67	2.67	8.59	3.64
36. Mississippi	500.6	5.30	2.65	6.24	2.28
37. Louisiana	614.1	2.20	0.44	3.01	-0.20
38. Arkansas	67.4	1.95	5.85	2.63	5.24
39. Arkansas SA*	10.6	2.40	7.20	2.40	6.66
40. Missouri	1290.5	2.58	11.06	3.38	11.00
41. Iowa	524.8	2.78	16.30	3.56	16.10

42.	Southern Illinois	1065.6	6.44	11.44	6.31	11.15
43.	Northern Illinois	959.9	7.42	14.42	6.97	14.43
44.	Northern Indiana	751.4	10.00	14.00	9.37	14.55
45.	Southern Indiana	1793.2	9.63	11.13	9.69	11.06
46.	Southern Ohio	3014.2	14.14	11.86	14.58	12.07
47.	Northeastern Ohio	1108.8	15.50	14.50	15.32	14.54
48.	Northwestern Ohio	635.9	12.78	13.33	13.06	13.07
49.	Southern Michigan	2310.5	12.17	16.67	12.71	16.16
50.	Northern Michigan	316.4	10.50	20.54	10.20	20.27
51.	Wisconsin	935.5	6.84	19.36	7.36	18.34
52.	Minnesota	487.3	2.15	20.51	3.54	20.91
53.	Boundary Waters SA*	20.2	6.20	24.60	6.00	24.00
54.	Central Ontario	433.5	12.52	23.57	16.00	20.99
55.	Sudbury	1060.8	15.00	21.00	15.00	21.00
56.	Ontario SA*	8.2	17.50	19.50	17.34	19.12
57.	Southern Ontario	585.4	17.12	17.76	16.25	17.27
58.	Quebec SA*	14.5	23.50	22.50	23.50	22.50
59.	Southern Quebec	273.0	22.69	21.00	23.10	20.66
60.	Central Quebec	732.9	23.66	24.33	19.12	24.23
61.	Southern Nova Scotia*	2.9	30.50	19.50	30.50	19.50
62.	Nova Scotia	--	32.00	21.50	32.00	21.50
63.	Newfoundland	--	37.00	28.00	37.00	28.00

*SA = Sensitive Area

NOTE: Canadian emissions in areas 54-60 are also from the SURE inventory.

TABLE A6-3 SURE II SO_2 Emissions Allocated to Grid Aggregate Areas Subdivided by by Stack Height

		STACK HEIGHT		TOTAL
Area Number	<100m	100m - 300m	>300m	(10^3 tons)
1	45	4	0	49
2	0	0	0	0
3	0	0	0	0
4	34	17	0	51
5	74	233	0	307
6	6	8	0	14
7	18	13	0	31
8	0	0	0	0
9	94	60	0	154
10	141	25	0	166
11	169	60	0	229
12	193	97	0	290
13	131	202	0	333
14	279	424	170	873
15	30	0	0	30
16	81	173	0	254
17	43	22	0	65
18	192	38	0	230
19	40	536	443	1019
20	45	109	0	154
21	170	413	0	583
22	217	561	248	1026
23	200	198	231	629
24	54	281	125	460
25	16	0	0	16
26	110	271	0	381
27	165	96	0	261
28	186	60	0	246
29	0	260	277	537
30	63	12	41	116
31	196	238	0	434
32	62	64	0	126
33	14	0	0	14
34	36	6	0	42
35	286	542	69	897
36	269	57	0	326
37	263	126	0	389
38	11	2	0	13
39	0	0	0	0
40	139	856	0	995
41	193	19	0	212

		STACK HEIGHT		TOTAL
Area Number	<100m	100m - 300m	>300m	(10^3 tons)
42	204	713	0	917
43	138	325	0	463
44	240	176	0	416
45	233	1254	0	1487
46	211	2048	403	2662
47	519	123	0	642
48	94	170	0	264
49	534	1253	0	1787
50	96	78	0	174
51	170	355	0	525
52	38	285	0	323
53	20	0	0	20
54	162	264	1059	1485
55	0	0	0	0
56	0	0	0	0
57	27	345	0	372
58	0	0	0	0
59	89	0	0	89
60	36	650	0	686
	7,076	14,122	3,066	24,264

FIGURE A6-1 SO$_2$ Emission Rate with Height (SURE II Inventory)

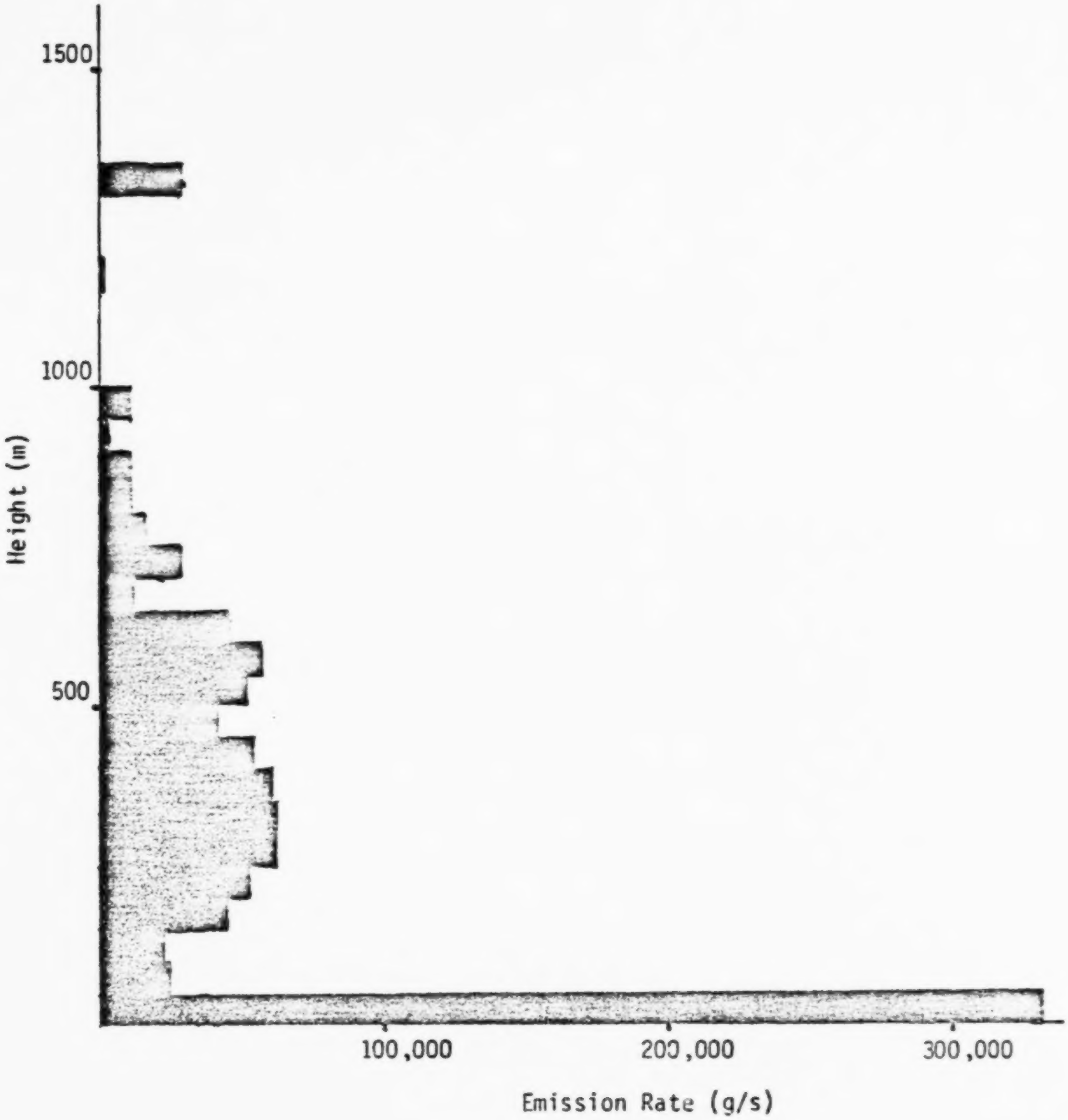


TABLE A6-4

Principal Reason for Selection of Sensitive Areas

AREA NUMBER	PRINCIPAL REASON
2	Hubbard Brook Studies by Likens et al
8	Lake Studies by Scofield, EPRI, etc.
15	River and Stream Studies by Arnold et al
25	Great Smoky Mountain National Park
33	Lake and Swamp Studies by Brezonik et al
39	Ozark Mountain Soils and Forests and Hot Springs National Park
53	Lake Studies by Gary Glass et al
56	Lake Studies by Canadians
58	Lake Studies by Canadians
61	Lake Studies by Canadians

TABLE A6-5 Relationship Between Area Numbers and Abbreviations on Large Map

Area Number	Map Designation
1	ME
2	SA1
3	VT
4	NH
5	MA
6	RI
7	CN
8	SA2
9	NY1
10	NY2
11	NJ
12	PA1
13	PA2
14	PA3
15	SA3
16	MD
17	DE
18	VA
19	WV1
20	WV2
21	KY1
22	KY2
23	TN1
24	TN2
25	SA4
26	NC1
27	NC2
28	SC
29	GA1
30	GA2
31	FL1
32	FL2
33	SA5
34	FL3
35	AL
36	MS
37	LA
38	AR
39	SA6
40	MO
41	IA
42	IL1
43	IL2
44	IN1
45	IN2
46	OH1
47	OH2
48	OH3
49	MI1
50	MI2
51	WI
52	MN
53	SA7
54	ON1
55	ON2
56	SA8
57	ON3
58	SA9
59	QE1
60	QE2
61	SA10
62	NS
63	NF

TABLE A6-6 Relationship Between Canadian Regions and the 63 Aggregated SURE Grid Areas

Canadian Region #	Area Represented	Canadian SO_2 Emissions(1) (kT/yr)	Canadian SO_2 Emissions(2) (kT/yr)	SURE SO_2 Emissions(3) (kt/yr)	Principal SURE Areas
1	Michigan	1946	1566	2627	49-50
	(South Michigan)	(1762)		(2311)	(49)
2	Illinois, Indiana	3874	5072	4570	42-45
	(Southern Illinois)	(1050)		(1066)	(42)
3	Ohio	4762	3961	4759	46-48
	(Southern Ohio)	(3092)		(3014)	(46)
	(Northeast Ohio)	(1286)		(1109)	(47)
4	Pennsylvania	2056	2039	2177	12-15
	(Western Pennsylvania)	(1067)		(1076)	(14)
5	New York, New Jersey		2281		
	to Maine	2408		2656	1-11
6	Kentucky, Tennessee	2835	2400	3241	21-25
	(Western Kentucky)	(740)		(1055)	(22)
7	West Virginia,				
	Virginia, N. Carolina,	2446	3400	2557	16-20
	Delaware, Maryland,				
	and D.C.			985	26-27
	(Northern W. Virginia)	(476)		(1086)	(19)
8	Rest of Eastern				
	United States	7485	2387	8803	28-41, 51, 52
	(Missouri)	(1316)		(1291)	(40)
	(Alabama)	(1525)		(1209)	(35)
	TOTAL EASTERN U.S.	27,812	23,106	32,375	
9	Ontario	1970	1809	2108	53-57
	(Sudbury)	(1001)		(1061)	(55)
10	Quebec	1037	1186	1021	58-60
11	Atlantic Provinces	469	368		
	TOTAL EASTERN CANADA	3,476	3,363	3129	

1 kT = 1.1 kt

[1] Used in AES-LRT Model
[2] Used in OME-LRT Model
[3] Used in ENAMAP, ASTRAP, and RCDM Models

TABLE A6-7 Relationship Between Canadian Receptor Areas and ARMS Sensitive Areas

ARMS Sensitive Area	Name	Canadian Receptor Point	Area Represented	Comments
1	New Hampshire	6	New Hampshire	
2	Adirondacks	7	Adirondack (Whiteface)	
3	Pennsylvania	8	Pennsylvania (Penn State)	in PA 2
4	Southern Appalachia	9	Southern Appalachia (Smokies)	
5	Florida			
6	Arkansas			
7	Boundary Waters	1	Boundary Waters	Northwest of SA 7
8	Ontario	3	Muskoka	
9	Quebec	4	Quebec City (Montmorency)	
10	Nova Scotia	5	Southern Nova Scotia	
		2	Algoma	

A6.2 Canadian Emissions - Current Data Base

The data base for current emission rates in Canada represents a mixture of information covering the period 1976 through 1980. For sulphur dioxide, all area source data represent 1976 annual emission rates (1). Major point sources are at their 1979 annual emission rate and the most important copper-nickel smelter complex, representing about twenty percent of eastern Canada emissions, is shown at its 1980 emission rate (2). On a weighted emissions basis the aggregated SO_2 data base closely represents actual emissions for the year 1979.

In the case of nitrogen oxides all area source type emissions are from the 1976 base year (1) and major point sources are at their 1979 annual emission rate (2). On a weighted emissions basis the aggregated Canadian NO_x data base probably represents actual emission rates in 1977.

The eastern Canada (including Manitoba) data is further prorated on a grid array of 127 km x 127 km squares which is the basic dimension for the emissions and meteorological data used in the AES long-range transport model.

On a national basis the overall accuracy of the current Canadian SO_2 emissions inventory is estimated to be + 30% at a 75% confidence level (2). The accuracy varies widely for each sector of emissions and within each sector, and is far greater for the major point sources (e.g. Cu-Ni smelters), which together represent more than half of total Canadian emissions, than for sources of lesser significance. An uncertainty analysis has not been carried out for NO_x emissions.

Seasonal variations data for use in detailed air quality analysis have been developed for both SO_2 and NO_x emissions for all contributing sectors (2). Nationwide inventories of the natural emissions of sulphur and nitrogen compounds have also been prepared (3,4)

References

1. Environment Canada, Air Pollution Control Directorate, A Nationwide Inventory of Emissions of Air Contaminants (1976), Report EPS-3-AP-80-1 (December 1980).
2. Environment Canada, Air Pollution Control Directorate, Data Analysis Division (Unpublished information) (December 1980)
3. Environment Canada, Air Pollution Control Directorate, National Inventory of Natural Sources and Emissions of Sulphur Compounds, Report EPS 3-APA-79-2 (February 1980)
4. Environment Canada, Air Pollution Control Directorate, National Inventory of Natural Sources and Emissions of Nitrogen Compounds, Report EPS 3-AP-80-4 (January 1981)

Appendix 7

Matrix Operations

A. MATRIX MANIPULATION PROGRAMS

The integrated analysis framework outlined in Table A7.1 has three major characteristics:

1. The ability to selectively combine information from various sources such as emission inventories and transport model transfer matrices to provide estimates of resulting concentrations and depositions.
2. The ability to support comparison and evaluation of different data bases and models by converting their results to common units and output formats.
3. The ability to combine emission projections with cost implications data in order to identify cost-effective answers to questions concerning how to reduce atmospheric loadings and/or deposition.

With regard to the first characteristic, the integrating framework could be used to combine utility, industrial, combustion, and area source emission estimates from different models in order to produce integrated emission estimates from all sectors. The emissions can then be combined with transfer matrices in order to estimate deposition.

With regard to the second characteristic, the integrating framework can be used in converting data from different sources to common units. For example, ENAMAP and ASTRAP results have been converted to common units and comparison tables and scatter diagrams prepared.

Table A.7-1 Integrated ARMS/RCG/MOI

SO$_x$ Source - Receptor Matrix Processing System

External - prepare inputs	Work Group 2 - analyze and intercompare	Work Groups 3A and 3B - develop least cost control strategy
Emissions and control costs		Program 4 - Format Emissions (4) and Costs
Utility - USM, ICF, EPA		
Industrial - ICF, IFCAM	Run models with emissions to meet specified target loadings in sensitive areas.	Program 5 - Least-Cost Source-Receptor Optimization (5)
Other - EPA Mobile, SEAS - DOE Canada - Work Group 3B	Re-run models to confirm efficacy of emission reduction scenarios to meet specified target loadings in sensitive areas.	
LRTAP model matrices	Program 1 - Format Matrices (1)	Program 3 - Compute Concentrations and Depositions (3)
Canadian - AES, OME (11x9x5)	Program 2 - Intercompare Matrices (2)	
U.S. - ENAMAP, ASTRAP* RCDM* (63x63x VAR)	2A Convert: U.S. to Canada	
Other - CAPITA*, REGMOD (episode), BWA, PNL, BNL	2B Plot Scatter Figures	
	Program 3 - Same as for Work Group 3A and 3B	

* NO$_x$ in progress

Status:
(1) on-line
(2) in-process
(3) on-line
(4) to be developed
(5) modify existing program

The final characteristic permits the combined assessment of emissions, costs of controling emissions, and resulting deposition. The development of cost-effective control strategies is done using a nonlinear optimization model which is being extended to consider regional scale problems. The optimization model identifies a least-cost solution which meets a combined set of emission quantity, ambient air quality, and/or deposition constraints.

B. TECHNIQUE FOR IDENTIFYING CANDIDATE AREAS FOR EMISSION REDUCTION

The deposition of sulphur D_j (or acid) at a receptor due to a source can be expressed as

$$D_j = Q_i f_{ij} \tag{1}$$

where Q_i is the strength of source 'i', and 'j' refers to the receptor. The transfer function f_{ij} establishes the physical relationship between the locations of the source and receptor. It is essentially the deposition at 'j' due to unit emissions at 'i' and is dependent on the scavenging and dispersion processes which affect the pollutants transported from 'i' to 'j'. f_{ij} is the most important model result from the point of view of emission control strategy.

The reduction in deposition $\widetilde{\Delta} D_j$ due to a source reduction ΔQ_i follows from (1)

$$\widetilde{\Delta} D_j = \Delta Q_i f_{ij} \tag{2}$$

The deposition reduction associated with a number of sources can be written as

$$\underset{i}{\Delta} D_j = \sum_i \Delta Q_i f_{ij} \qquad (3)$$

Equation (3) can be conveniently written for several receptors in matrix notation

$$\Delta D = F^T \Delta Q \qquad (4)$$

where ΔD and ΔQ are column vectors and F is the so-called transfer matrix and F^T is its transpose.

APPLICATIONS OF EQUATION (4)

There are any number of ways of looking at emission reduction scenarios. Some possible methods are

1) Maximize the reduction in deposition given constraints on emission reduction. This is a problem in linear programming and can be stated as:

$$\text{Maximize} \quad \Delta D = \sum_j \sum_i \Delta Q_i f_{ij} a_j \qquad (5a)$$

$$\text{Given} \sum \alpha_{ij} \Delta Q_i \leq Q_{Tj}; \quad j = 1,2....N \qquad (5b)$$

where Q_{Tj} is the specified emission constraint and N is the number of constraints. The number a_j reflects the importance assigned by the decision maker to the receptor j. For example, the Ontario Ministry of the Environment might want to give Ontario receptors three times more importance than the other receptors of interest. Then we take $a_j = 3$ for Ontario receptors and $a_j = 1$ for the others.

2) Minimize cost of emission reduction given constraints on deposition reduction. This is also a problem in linear programming which can be stated as

$$\text{Minimize } \Delta C = \sum_i b_i \Delta Q_i \tag{6a}$$

$$\text{Given } \sum_i \beta_{ij} \Delta D_i \geq \Delta D_{Tj};\ j = 1,2....N \tag{6b}$$

where b_i relates cost to emission reduction. A possible constraint corresponding to (6b) is

$$\Delta D_i \geq \Delta D_{Ti} \tag{7}$$

Equation (7) states that the deposition reduction at each receptor should be greater than or equal to a specified value. Note that ΔD_i in (6b) is related to ΔQ_j through (2).

This discussion illustrates the importance of the transfer matrix F in any emission reduction strategy.

Another important "effect" variable is the frequency with which a concentration or deposition is exceeded at a receptor of interest. If we denote this frequency by $F_{ij}(c)$ we can write

$$F_{ij}(c) = \Psi(Q_i, D_{ij}) \qquad (8)$$

Note that F_{ij} is not expected to be a linear function of Q_i. D_{ij} is the physical relationship between 'i' and 'j' which can derived from Lagrangian model results for time scales for which the concentration is important. Clearly the use of (8) in emission control strategy requires non-linear optimization techniques.

Appendix 8

Transfer Matrices

NOTE: An addendum to this appendix containing the ASTRAP, ENAMAP, and RCDM model matrices is in process.

Table A8-1 Transfer Matrix of:

Annual Sulfur Dioxide Concentration (ug/m^{-3})
per unit emission (Tg.S.yr^{-1})

Source Regions	Models	Emiss. (Tg.S)	Receptor Areas								
			B.Waters (1)	Alg. (2)	Musk. (3)	Que. (4)	S. N.Sc. (5)	Vt. NH. (6)	Adir. (7)	Penn. (8)	Smokies (9)
1 Mich.	MOE	0.784	0.08	0.70	1.7	0.50	0.57	0.91	1.5	3.3	0.16
	AES	0.973	0.16	2.9	4.4	0.80	0.38	1.0	1.4	3.8	0.16
2 Ill. Ind.	MOE	2.538	0.07	0.34	0.49	0.19	0.22	0.31	0.46	1.3	0.80
	AES	1.937	0.07	0.72	0.77	0.15	0.11	0.26	0.42	1.2	1.6
3 Ohio	MOE	1.983	0.04	0.22	0.51	0.25	0.40	0.48	0.78	4.0	0.37
	AES	2.381	0	0.14	1.2	0.40	0.32	0.71	1.3	9.0	0.80
4 Penn.	MOE	1.021	0.03	0.17	0.46	0.30	0.62	0.63	0.99	9.2	0.16
	AES	1.028	0	.06	0.71	0.47	0.44	1.3	2.2	21.7	0.12
5 N.York to Maine	MOE	1.143	0.02	0.10	0.33	0.40	1.9	1.0	1.6	0.62	0.06
	AES	1.204	0.01	0.12	0.56	0.91	4.2	2.0	3.2	0.58	0.04
6 Kent. Tenn.	MOE	1.202	0.03	0.12	0.19	0.10	0.15	0.17	0.23	0.74	3.2
	AES	1.418	0	0.07	0.27	0.04	0.04	0.12	0.22	1.3	9.3
7 W.Virg. to N.C.	MOE	1.703	0.02	0.10	0.22	0.17	0.40	0.33	0.46	1.7	0.26
	AES	1.223	0	0.02	0.16	0.16	0.18	0.38	0.64	3.0	0.90
8 Rest of (USA) Fld to Mo. to Minn.	MOE	1.196	0.12	0.68	0.55	0.20	0.18	0.28	0.38	0.62	1.9
	AES	3.743	0.53	0.61	0.27	0.05	0.03	0.07	0.13	0.45	3.0
9 Ontario	MOE	0.906	0.10	1.0	3.2	1.9	0.91	2.0	2.2	0.96	0.06
	AES	0.985	0.11	2.5	12.4	1.7	0.78	2.6	4.2	2.4	0.08
10 Quebec	MOE	0.595	0.06	0.30	0.57	3.0	1.3	4.7	1.1	0.18	0.03
	AES	0.519	0.08	0.91	1.9	6.7	2.3	13.1	3.9	0.29	0.02
11 Atlantic Provinces	MOE	0.187	0.01	0.03	0.07	0.26	1.5	0.26	0.15	0.05	0.01
	AES	0.235	0	0	0.04	0.26	13.6	0.13	0.09	0	0

Table A8-2 Transfer Matrix of:

Annual Sulfate Concentration (ug/m^{-3})
per unit emission (TgS.yr^{-1})

			Receptor Areas								
Source Regions	Models	Emiss. (Tg.S)	B.Waters (1)	Alg. (2)	Musk. (3)	Que. (4)	S. N.Sc. (5)	Vt. NH. (6)	Adir. (7)	Penn. (8)	Smokies (9)
1 Mich.	MOE	0.784	0.08	0.27	0.56	0.32	0.38	0.46	0.61	0.86	0.13
	AES	0.973	0.10	0.45	1.8	0.55	0.46	0.80	0.94	1.5	0.25
2 Ill. Ind.	MOE	2.538	0.08	0.22	0.29	0.18	0.22	0.25	0.31	0.57	0.36
	AES	1.937	0.02	0.37	0.41	0.12	0.11	0.22	0.34	0.72	1.3
3 Ohio	MOE	1.983	0.06	0.15	0.26	0.20	0.30	0.30	0.38	0.88	0.19
	AES	2.381	0	0.04	0.59	0.16	0.31	0.41	0.63	2.3	0.63
4 Penn.	MOE	1.021	0.05	0.12	0.23	0.21	0.37	0.33	0.41	1.1	0.12
	AES	1.028	0	0.03	0.29	0.20	0.34	0.50	0.91	2.5	0.11
5 N.York to Maine	MOE	1.143	0.04	0.08	0.15	0.22	0.61	0.35	0.38	0.19	0.06
	AES	1.204	0.01	0.08	0.22	0.31	1.2	0.55	0.70	0.18	0.02
6 Kent. Tenn.	MOE	1.202	0.05	0.12	0.16	0.12	0.17	0.17	0.20	0.38	0.07
	AES	1.418	0	0.04	0.12	0.01	0.04	0.06	0.11	0.56	2.6
7 W.Virg. to N.C.	MOE	1.703	0.04	0.09	0.16	0.15	0.28	0.22	0.26	0.42	0.13
	AES	1.223	0	0	0.07	0.05	0.13	0.17	0.27	0.90	0.70
8 Rest of (USA) Fld to Mo. to Minn.	MOE	1.196	0.09	0.27	0.29	0.17	0.19	0.22	0.26	0.35	0.44
	AES	3.743	0.12	0.27	0.20	0.05	0.05	0.08	0.13	0.29	1.2
9 Ontario	MOE	0.906	0.08	0.23	0.67	0.66	0.49	0.69	0.69	0.34	0.07
	AES	0.985	0.05	0.67	2.3	1.0	0.79	1.4	1.9	1.0	0.11
10 Quebec	MOE	0.595	0.06	0.14	0.22	0.72	0.51	.75	0.34	0.14	0.04
	AES	0.519	0.14	0.42	0.85	1.3	1.2	1.9	1.4	0.17	0.04
11 Atlantic Provinces	MOE	0.187	0.02	0.04	0.06	0.13	0.33	0.13	0.10	0.06	0.03
	AES	0.235	0	0	0	0.13	0.55	0.04	0.04	0	0

Table A8-3 Transfer Matrix of:

Annual Dry Deposition of Sulfur ($kg.ha^{-1}.yr^{-1}$) per unit emission ($Tg.S.yr^{-1}$)

			Receptor Areas								
Source Regions	Models	Emiss. (Tg.S)	B.Waters (1)	Alg. (2)	Musk. (3)	Que. (4)	S. N.Sc. (5)	Vt. NH. (6)	Adir. (7)	Penn. (8)	Smokies (9)
1 Mich.	MOE	0.784	0.07	0.56	1.4	0.41	0.46	0.73	1.2	2.6	0.13
	AES	0.973	0.10	2.3	3.7	0.72	0.31	0.92	1.2	3.1	0.10
2 Ill. Ind.	MOE	2.538	0.05	0.28	0.39	0.16	0.18	0.25	0.37	1.0	0.64
	AES	1.937	0.10	0.62	0.62	0.16	0.10	0.21	0.36	1.0	1.4
3 Ohio	MOE	1.983	0.04	0.18	0.41	0.20	0.32	0.39	0.62	3.1	0.30
	AES	2.381	0	0.13	0.97	0.29	0.29	0.63	1.1	7.4	0.67
4 Penn.	MOE	1.021	0.03	0.14	0.36	0.24	0.49	0.50	0.79	7.2	0.13
	AES	1.028	0	0.10	0.58	0.39	0.39	1.1	1.8	17.4	0.10
5 N.York to Maine	MOE	1.143	0.02	0.08	0.26	0.32	1.5	0.82	1.2	0.49	0.05
	AES	1.204	0	0.08	0.50	0.75	3.4	1.7	2.7	0.50	0
6 Kent. Tenn.	MOE	1.202	0.03	0.10	0.15	0.08	0.13	0.14	0.19	0.59	2.5
	AES	1.418	0	0.07	0.21	0	0.07	0.07	0.21	1.1	7.6
7 W.Virg. to N.C.	MOE	1.703	0.02	0.08	0.18	0.14	0.32	0.26	0.37	1.3	0.21
	AES	1.223	0	0	0.16	0.16	0.16	0.33	0.48	2.5	0.74
8 Rest of (USA) Fld to Mo. to Minn.	MOE	1.196	0.10	0.54	0.44	0.16	0.15	0.22	0.31	0.50	1.5
	AES	3.743	0.43	0.51	0.24	0.05	0.03	0.05	0.11	0.37	2.5
9 Ontario	MOE	0.906	0.08	0.79	2.5	1.5	0.73	1.5	1.7	0.76	0.05
	AES	0.985	0.10	2.0	9.9	1.4	0.71	2.2	3.4	2.0	0.10
10 Quebec	MOE	0.595	0.05	0.24	0.45	2.3	1.0	3.7	0.86	0.15	0.02
	AES	0.519	0	0.77	1.7	5.4	1.9	10.6	3.3	0.19	0
11 Atlantic Provinces	MOE	0.187	0.01	0.03	0.05	0.21	1.2	0.21	0.12	0.04	0.01
	AES	0.235	0	0	0	0.43	10.6	0	0	0	0

Table A8-4 Transfer Matrix of:

Annual Wet Deposition of Sulfur ($kg.ha^{-1}.yr^{-1}$)
per unit emission ($Tg.S.yr^{-1}$)

			Receptor Areas								
Source Regions	Models	Emiss. (Tg.S)	B.Waters (1)	Alg. (2)	Musk. (3)	Que. (4)	S. N.Sc. (5)	Vt. NH. (6)	Adir. (7)	Penn. (8)	Smokies (9)
1 Mich.	MOE	0.784	0.07	0.40	0.93	0.34	0.39	0.56	0.86	1.7	0.12
	AES	0.973	0.21	2.4	3.2	1.0	0.31	0.72	1.1	1.7	0.21
2 Ill. Ind.	MOE	2.538	0.06	0.23	0.32	0.15	0.18	0.23	0.31	0.76	0.47
	AES	1.937	0.05	1.2	1.1	0.31	0.10	0.30	0.36	1.1	0.77
3 Ohio	MOE	1.983	0.04	0.15	0.32	0.19	0.28	0.32	0.47	2.0	0.23
	AES	2.381	0	0.25	1.8	0.46	0.21	1.0	1.3	4.7	0.25
4 Penn.	MOE	1.021	0.03	0.12	0.28	0.21	0.40	0.39	0.57	4.4	0.11
	AES	1.028	0	0.29	1.3	0.68	0.29	1.8	2.2	7.9	0.10
5 N.York to Maine	MOE	1.143	0.02	0.07	0.19	0.25	1.0	0.56	0.80	0.33	0.05
	AES	1.204	0	0.17	0.50	1.3	2.0	2.2	2.4	0.42	0
6 Kent. Tenn.	MOE	1.202	0.03	0.10	0.14	0.09	0.13	0.14	0.18	0.46	1.6
	AES	1.418	0	0.14	0.71	0.07	0.07	0.21	0.42	1.5	3.1
7 W.Virg. to N.C.	MOE	1.703	0.03	0.08	0.15	0.13	0.28	0.22	0.29	0.85	0.16
	AES	1.223	0	0	0.33	0.33	0.25	0.90	1.1	3.5	0.49
8 Rest of (USA) Fld to Mo. to Minn.	MOE	1.196	0.09	0.39	0.34	0.15	0.15	0.20	0.26	0.40	1.0
	AES	3.743	0.24	0.61	0.24	0.05	0.03	0.08	0.13	0.53	2.5
9 Ontario	MOE	0.906	0.08	0.51	1.6	1.0	0.57	1.1	1.2	0.53	0.05
	AES	0.985	0.10	1.8	3.3	1.7	0.61	1.6	2.0	1.2	0
10 Quebec	MOE	0.595	0.06	0.18	0.32	1.5	0.73	2.3	0.59	0.13	0.03
	AES	0.519	0	0.19	0.58	2.9	0.96	3.3	1.5	0.19	0
11 Atlantic Provinces	MOE	0.187	0.01	0.03	0.05	0.16	0.74	0.16	0.10	0.05	0.01
	AES	0.235	0	0	0	0.43	2.6	0	0	0	0

Table A8-5 Transfer Matrix of:

Annual Total Deposition of Sulfur (kg.ha^{-1}.yr^{-1})
per unit emission (Tg.S.yr^{-1})

			Receptor Areas								
Source Regions	Models	Emiss. (Tg.S)	B.Waters (1)	Alg. (2)	Musk. (3)	Que. (4)	S. N.Sc. (5)	Vt. NH. (6)	Adir. (7)	Penn. (8)	Smokies (9)
1 Mich.	MOE	0.784	0.13	0.96	2.3	0.74	0.84	1.3	2.0	4.3	0.25
	AES	0.973	0.31	4.6	6.9	1.7	0.62	1.6	2.3	4.8	0.31
2 Ill. Ind.	MOE	2.538	0.11	0.50	0.71	0.31	0.37	0.48	0.68	1.8	1.1
	AES	1.937	0.16	1.8	1.8	0.41	0.21	0.47	0.72	2.2	2.2
3 Ohio	MOE	1.983	0.08	0.33	0.72	0.39	0.61	0.71	1.1	5.2	0.52
	AES	2.381	0	0.38	2.8	0.76	0.50	1.6	2.5	12.1	0.92
4 Penn.	MOE	1.021	0.06	0.26	0.64	0.45	0.89	0.88	1.4	11.6	0.24
	AES	1.028	0	0.39	1.8	1.2	0.68	2.7	4.2	25.3	0.20
5 N.York to Maine	MOE	1.143	0.04	0.16	0.46	0.57	2.5	1.4	2.0	0.82	0.10
	AES	1.204	0	0.33	1.0	2.1	5.4	3.9	5.1	0.91	0
6 Kent. Tenn.	MOE	1.202	0.06	0.19	0.30	0.17	0.26	0.27	0.37	1.0	4.2
	AES	1.418	0	0.21	0.92	0.07	0.14	0.28	0.64	2.5	10.7
7 W.Virg. to N.C.	MOE	1.703	0.04	0.16	0.33	0.27	0.60	0.49	0.66	2.2	0.37
	AES	1.223	0	0.08	0.41	0.49	0.41	1.2	1.6	6.0	1.2
8 Rest of (USA) Fld to Mo. to Minn.	MOE	1.196	0.19	0.93	0.78	0.31	0.30	0.43	0.57	0.90	2.4
	AES	3.743	0.67	1.1	0.48	0.11	0.08	0.13	0.24	0.91	5.0
9 Ontario	MOE	0.906	0.16	1.3	4.1	2.5	1.3	2.6	2.9	1.3	0.10
	AES	0.985	0.10	4.0	13.4	3.1	1.3	3.8	5.5	3.1	0.10
10 Quebec	MOE	0.595	0.11	0.42	0.77	3.8	1.7	6.1	1.5	0.28	0.05
	AES	0.519	0.19	0.96	2.3	8.3	2.9	13.9	4.8	0.39	0
11 Atlantic Provinces	MOE	0.187	0.02	0.06	0.11	0.36	1.9	0.37	0.23	0.09	0.02
	AES	0.235	0	0	0	0.43	13.6	0.43	0	0	0

Table A8-6 Transfer Matrix of:

Annual Sulfur Dioxide Concentration (ug.m^{-3})

Source Regions	Models	Receptor Areas								
		B.Waters (1)	Alg. (2)	Musk. (3)	Que. (4)	S. N.Sc. (5)	Vt. NH. (6)	Adir. (7)	Penn. (8)	Smokies (9)
1 Mich.	MOE	0.06	0.55	1.4	0.39	0.44	0.71	1.2	2.6	0.12
	AES	0.16	2.8	4.3	0.78	0.37	1.0	1.4	3.7	0.16
2 Ill. Ind.	MOE	0.18	0.87	1.2	0.48	0.57	0.78	1.2	3.3	2.0
	AES	0.14	1.4	1.5	0.29	0.21	0.50	0.81	2.3	3.2
3 Ohio	MOE	0.08	0.43	1.0	0.50	0.79	0.95	1.5	7.9	0.73
	AES	0	0.33	2.8	0.88	0.77	1.7	3.2	21.5	1.9
4 Penn.	MOE	0.03	0.17	0.46	0.30	0.63	0.63	1.0	9.4	0.16
	AES	0	0.06	0.73	0.48	0.45	1.3	2.3	22.3	0.12
5 N.York to Maine	MOE	0.02	0.11	0.37	0.46	2.1	1.2	1.8	0.71	0.07
	AES	0.01	0.15	0.68	1.1	5.1	2.4	3.9	0.70	0.05
6 Kent. Tenn.	MOE	0.04	0.14	0.22	0.12	0.18	0.20	0.28	0.89	3.9
	AES	0	0.10	0.38	0.06	0.06	0.17	0.31	1.8	13.2
7 W.Virg. to N.C.	MOE	0.04	0.17	0.38	0.29	0.68	0.56	0.78	2.8	0.44
	AES	0	0.02	0.20	0.19	0.22	0.46	0.78	3.7	1.1
8 Rest of (USA) Fld to Mo. to Minn.	MOE	0.15	0.81	0.66	0.24	0.22	0.33	0.45	0.75	2.2
	AES	2.0	2.3	1.0	0.17	0.13	0.26	0.47	1.7	11.4
9 Ontario	MOE	0.09	0.91	2.9	1.7	0.82	1.8	2.0	0.87	0.05
	AES	0.11	2.5	12.2	1.7	0.77	2.6	4.1	2.4	0.08
10 Quebec	MOE	0.04	0.18	0.34	1.8	0.76	2.8	0.65	0.11	0.02
	AES	0.04	0.47	1.0	3.5	1.2	6.8	2.0	0.15	0.01
11 Atlantic Provinces	MOE	0	0.01	0.01	0.05	0.27	0.05	0.03	0.01	0
	AES	0	0	0.01	0.06	3.2	0.03	0.02	0	0
Western Canada	AES	0.48	0.14	0.06	0.01	0.01	0.02	0.01	0	0
Total Concentration	MOE	0.73	4.4	8.9	6.3	7.5	10.0	10.9	29.4	9.7
	AES	2.9	10.3	24.9	9.2	12.5	17.3	19.3	60.3	31.2

Table A8-7 Transfer Matrix of:

Annual Sulfate Concentration (ug m-3)

Source Regions	Models	Receptor Areas B.Waters (1)	Alg. (2)	Musk. (3)	Que. (4)	S. N.Sc. (5)	Vt. NH. (6)	Adir. (7)	Penn. (8)	Smokies (9)
1 Mich.	MOE	0.06	0.21	0.44	0.25	0.30	0.36	0.48	0.67	0.10
	AES	0.10	0.44	1.8	0.54	0.45	0.78	0.91	1.5	0.24
2 Ill. Ind.	MOE	0.20	0.54	0.75	0.46	0.56	0.63	0.79	1.4	0.91
	AES	0.04	0.71	0.79	0.24	0.21	0.42	0.65	1.4	2.5
3 Ohio	MOE	0.11	0.30	0.52	0.40	0.59	0.60	0.76	1.7	0.38
	AES	0	0.10	1.4	0.39	0.74	0.97	1.5	5.5	1.5
4 Penn.	MOE	0.05	0.13	0.23	0.22	0.38	0.34	0.42	1.2	0.12
	AES	0	0.03	0.30	0.20	0.35	0.51	0.93	2.6	0.11
5 N.York to Maine	MOE	0.04	0.09	0.17	0.25	0.70	0.40	0.44	0.21	0.07
	AES	0.01	0.09	0.26	0.37	1.5	0.66	0.84	0.22	0.02
6 Kent. Tenn.	MOE	0.06	0.14	0.20	0.15	0.20	0.20	0.24	0.46	0.84
	AES	0	0.05	0.17	0.01	0.06	0.08	0.16	0.80	3.7
7 W.Virg. to N.C.	MOE	0.06	0.16	0.26	0.26	0.47	0.38	0.44	0.72	0.23
	AES	0	0	0.09	0.06	0.16	0.21	0.33	1.1	0.86
8 Rest of (USA) Fld to Mo. to Minn.	MOE	0.11	0.32	0.34	0.21	0.22	0.26	0.31	0.42	0.52
	AES	0.44	1.0	0.74	0.18	0.17	0.28	0.48	1.1	4.3
9 Ontario	MOE	0.07	0.21	0.60	0.60	0.45	0.63	0.62	0.31	0.06
	AES	0.05	0.66	2.3	0.98	0.78	1.4	1.9	1.0	0.11
10 Quebec	MOE	0.04	0.08	0.13	0.43	0.31	0.44	0.20	0.08	0.03
	AES	0.07	0.22	0.44	0.66	0.63	0.98	0.75	0.09	0.02
11 Atlantic Provinces	MOE	0	0.01	0.01	0.02	0.06	0.02	0.02	0.01	0
	AES	0	0	0	0.03	0.13	0.01	0.01	0	0
Western Canada	AES	0.40	0.20	0.09	0.07	0.06	0.06	0.04	0.03	0
Total Concen-tration	MOE	0.80	2.2	3.7	3.3	4.3	4.3	4.7	7.2	3.3
	AES	1.1	3.5	8.4	3.7	5.2	6.4	8.5	15.3	13.3

Table A8-8 Transfer Matrix of:

Annual Dry Deposition of Sulfur (kg.ha^{-1}.yr^{-1})

Source Regions	Models	Receptor Areas								
		B.Waters (1)	Alg. (2)	Musk. (3)	Que. (4)	S. N.Sc. (5)	Vt. NH. (6)	Adir. (7)	Penn. (8)	Smokies (9)
1 Mich.	MOE	0.05	0.44	1.1	0.32	0.36	0.57	0.93	2.0	0.10
	AES	0.10	2.2	3.6	0.70	0.30	0.90	1.2	3.0	0.10
2 Ill. Ind.	MOE	0.13	0.70	0.99	0.40	0.47	0.63	0.94	2.6	1.6
	AES	0.20	1.2	1.2	0.30	0.20	0.40	0.70	2.0	2.8
3 Ohio	MOE	0.08	0.35	0.81	0.41	0.64	0.77	1.2	6.2	0.58
	AES	0	0.30	2.3	0.70	0.70	1.5	2.7	17.6	1.6
4 Penn.	MOE	0.03	0.14	0.37	0.24	0.50	0.51	0.80	7.3	0.13
	AES	0	0.10	0.60	0.40	0.40	1.1	1.9	17.9	0.10
5 N.York to Maine	MOE	0.02	0.09	0.30	0.37	1.7	0.94	1.4	0.56	0.05
	AES	0	0.10	0.60	0.90	4.1	2.0	3.2	0.60	0
6 Kent. Tenn.	MOE	0.03	0.12	0.18	0.10	0.15	0.16	0.23	0.71	3.1
	AES	0	0.10	0.30	0	0.10	0.10	0.30	1.5	10.8
7 W.Virg. to N.C.	MOE	0.03	0.14	0.31	0.24	0.55	0.45	0.63	2.2	0.35
	AES	0	0	0.20	0.20	0.20	0.40	0.60	3.0	0.90
8 Rest of (USA) Fld to Mo. to Minn.	MOE	0.12	0.65	0.53	0.19	0.18	0.27	0.37	0.60	1.8
	AES	1.6	1.9	0.9	0.20	0.10	0.20	0.40	1.4	9.5
9 Ontario	MOE	0.08	0.71	2.2	1.3	0.66	1.4	1.6	0.69	0.04
	AES	0.10	2.0	9.8	1.4	0.70	2.2	3.4	2.0	0.10
10 Quebec	MOE	0.03	0.14	0.27	1.4	0.60	2.2	0.51	0.09	0.01
	AES	0	0.40	0.90	2.8	1.0	5.5	1.7	0.10	0
11 Atlantic Provinces	MOE	0	0	0.01	0.04	0.22	0.04	0.02	0.01	0
	AES	0	0	0	0.10	2.5	0	0	0	0
Western Canada	AES	0.40	0.10	0.10	0	0	0	0	0	0
Total Concentration	MOE	0.60	3.5	7.1	5.0	6.0	7.9	8.6	23.0	7.7
	AES	2.4	8.4	20.5	7.7	10.3	14.3	16.1	49.1	25.9

Table A8-9 Transfer Matrix of:

Annual Wet Deposition of Sulfur (kg.ha^{-1}.yr^{-1})

		Receptor Areas								
Source Regions	Models	B.Waters (1)	Alg. (2)	Musk. (3)	Que. (4)	S. N.Sc. (5)	Vt. NH. (6)	Adir. (7)	Penn. (8)	Smokies (9)
1 Mich.	MOE	0.05	0.31	0.73	0.26	0.30	0.44	0.67	1.3	0.09
	AES	0.20	2.3	3.1	1.0	0.30	0.70	1.1	1.7	0.20
2 Ill. Ind.	MOE	0.15	0.58	0.81	0.39	0.46	0.58	0.79	1.9	1.2
	AES	0.10	2.4	2.2	0.60	0.20	0.50	0.70	2.2	1.5
3 Ohio	MOE	0.08	0.30	0.63	0.37	0.56	0.63	0.93	4.0	0.45
	AES	0	0.60	4.4	1.1	0.50	2.4	3.2	11.3	0.60
4 Penn.	MOE	0.03	0.12	0.28	0.21	0.41	0.40	0.58	4.5	0.11
	AES	0	0.20	1.3	0.70	0.30	1.8	2.3	8.1	0.10
5 N.York to Maine	MOE	0.03	0.09	0.22	0.29	1.2	0.64	0.91	0.38	0.06
	AES	0	0.20	0.60	1.6	2.4	2.7	2.9	0.50	0
6 Kent. Tenn.	MOE	0.04	0.12	0.17	0.11	0.16	0.16	0.21	0.55	2.0
	AES	0	0.20	1.0	0.10	0.10	0.30	0.60	2.1	4.4
7 W.Virg. to N.C.	MOE	0.04	0.13	0.26	0.22	0.47	0.38	0.50	1.5	0.27
	AES	0	0	0.40	0.40	0.30	1.1	1.4	4.3	0.60
8 Rest of (USA) Fld to Mo. to Minn.	MOE	0.10	0.46	0.41	0.18	0.18	0.24	0.31	0.47	1.1
	AES	0.90	2.3	0.90	0.20	0.10	0.30	0.50	2.0	9.2
9 Ontario	MOE	0.07	0.46	1.4	0.94	0.52	0.97	1.1	0.48	0.05
	AES	0.10	1.8	3.3	1.7	0.60	1.6	2.0	1.2	0
10 Quebec	MOE	0.03	0.11	0.19	0.90	0.43	1.4	0.35	0.08	0.02
	AES	0	0.10	0.30	1.5	0.50	1.7	0.80	0.10	0
11 Atlantic Provinces	MOE	0	0.01	0.01	0.03	0.14	0.03	0.02	0.01	0
	AES	0	0	0	0.10	0.60	0	0	0	0
Western Canada	AES	0.20	0.20	0.10	0	0	0	0.20	0	0
Total Concentration	MOE*	0.62	2.7	5.1	3.9	4.8	5.9	6.3	15.2	5.4
	AES	1.5	10.4	17.6	9.0	5.9	13.1	15.7	33.5	16.7

*Note: In order to calculate the total deposition at each site, the deposition resulting from background in the amount of 0.2 g.m^{-2}.yr^{-1} (or 2.0 kg.ha^{-1}.yr^{-1}) should be added to this row.

Table A8-10 Transfer Matrix of:

Total Annual Sulfur Deposition (kg.ha^{-1}.yr^{-1})

		Receptor Areas								
Source Regions	Models	B.Waters (1)	Alg. (2)	Musk. (3)	Que. (4)	S. N.Sc. (5)	Vt. NH. (6)	Adir. (7)	Penn. (8)	Smokies (9)
1 Mich.	MOE	0.10	0.75	1.8	0.58	0.66	1.0	1.6	3.4	0.19
	AES	0.30	4.5	6.7	1.7	0.60	1.6	2.2	4.7	0.30
2 Ill. Ind.	MOE	0.28	1.3	1.8	0.78	0.93	1.2	1.7	4.5	2.8
	AES	0.30	3.5	3.4	0.80	0.40	0.90	1.4	4.2	4.3
3 Ohio	MOE	0.16	0.65	1.4	0.77	1.2	1.4	2.2	10.2	1.0
	AES	0	0.90	6.7	1.8	1.2	3.9	5.9	28.9	2.2
4 Penn.	MOE	0.06	0.26	0.65	0.46	0.91	0.90	1.4	11.8	0.24
	AES	0	0.40	1.9	1.2	0.70	2.8	4.3	26.0	0.20
5 N.York to Maine	MOE	0.05	0.18	0.52	0.66	2.8	1.6	2.3	0.93	0.11
	AES	0	0.40	1.2	2.5	6.5	4.7	6.1	1.1	0
6 Kent. Tenn.	MOE	0.07	0.23	0.35	0.21	0.31	0.33	0.44	1.3	5.0
	AES	0	0.30	1.3	0.10	0.20	0.40	0.90	3.6	15.2
7 W.Virg. to N.C.	MOE	0.08	0.27	0.57	0.46	1.0	0.83	1.1	3.7	0.62
	AES	0	0.10	0.50	0.60	0.50	1.5	2.0	7.3	1.5
8 Rest of (USA) Fld to Mo. to Minn.	MOE	0.22	1.1	0.94	0.37	0.36	0.51	0.68	1.1	2.9
	AES	2.5	4.2	1.8	0.40	0.30	0.50	0.90	3.4	18.7
9 Ontario	MOE	0.14	1.2	3.7	2.3	1.2	2.4	2.6	1.2	0.09
	AES	0.10	3.9	13.2	3.1	1.3	3.8	5.4	3.1	0.10
10 Quebec	MOE	0.06	0.25	0.46	2.3	1.0	3.6	0.86	0.17	0.03
	AES	0.10	0.50	1.2	4.3	1.5	7.2	2.5	0.20	0
11 Atlantic Provinces	MOE	0	0.01	0.02	0.07	0.35	0.07	0.04	0.02	0
	AES	0	0	0	0.10	3.2	0.10	0	0	0
Western Canada	AES	0.60	0.20	0.20	0	0	0	0.20	0	0
Total Concentration	MOE*	1.2	6.2	12.2	8.9	10.8	13.8	14.9	38.3	13.0
	AES	3.9	18.8	38.1	16.7	16.3	27.4	31.8	82.5	42.6

*Note: In order to calculate the total deposition at each site, the deposition resulting from background in the amount of 0.2 g.m^{-2}.yr^{-1} (or 2.0 kg.ha^{-1}.yr^{-1}) should be added to this row.

Table A8-11 Transfer Matrix of:

Percent Contribution to Annual Sulphur Dioxide Concentration

		Receptor Areas								
Source Regions	Models	B.Waters (1)	Alg. (2)	Musk. (3)	Que. (4)	S. N.Sc. (5)	Vt. NH. (6)	Adir. (7)	Penn. (8)	Smokies (10)
1 Mich.	MOE	8.2	12.6	15.7	6.2	5.9	7.1	11.0	8.8	1.2
	AES	5.4	27.2	17.3	8.5	3.0	5.8	7.2	6.1	0.5
2 Ill. Ind.	MOE	24.7	19.8	13.4	7.6	7.6	7.8	11.0	11.2	20.6
	AES	4.8	13.6	6.0	3.2	1.7	2.9	4.2	3.8	10.3
3 Ohio	MOE	11.0	9.8	11.2	7.9	10.6	9.5	13.8	26.9	7.5
	AES	0	3.2	11.2	9.6	6.2	9.8	16.6	35.7	6.1
4 Penn.	MOE	4.1	3.9	5.2	4.8	8.4	6.3	9.2	32.0	1.7
	AES	0	0.6	2.9	5.2	3.6	7.5	11.9	37.0	0.4
5 N.York to Maine	MOE	2.7	2.5	4.2	7.3	28.0	12.0	16.5	2.4	0.7
	AES	0.3	1.5	2.7	11.9	40.8	13.9	20.2	1.2	0.1
6 Kent. Tenn.	MOE	5.5	3.2	2.4	1.9	2.4	2.0	2.6	3.0	40.2
	AES	0	1.0	1.5	0.7	0.4	1.0	1.6	3.0	42.3
7 W.Virg. to N.C.	MOE	5.5	3.9	4.3	4.6	9.1	5.6	7.2	9.5	4.5
	AES	0	0.2	0.8	2.1	1.7	2.7	4.0	6.1	3.5
8 Rest of (USA) Fld to Mo. to Minn.	MOE	20.5	18.5	7.4	3.8	2.9	3.3	4.1	2.6	22.7
	AES	68.0	22.3	4.0	1.9	1.0	1.5	2.4	2.8	36.5
9 Ontario	MOE	12.3	20.7	32.5	26.9	11.0	18.0	18.3	3.0	0.5
	AES	3.7	24.3	49.0	18.4	6.2	15.0	21.2	4.0	3.0
10 Quebec	MOE	5.5	4.1	3.8	28.5	10.1	28.0	6.0	0.4	0.2
	AES	1.4	4.6	4.0	38.0	9.6	39.3	10.4	0.3	0
11 Atlantic Provinces	MOE	0	0.2	0.1	0.8	3.6	0.5	0.3	0	0
	AES	0	0	0	0.7	25.6	0.2	0.1	0	0
Western Canada	AES	16.3	1.4	0.3	0.1	0.1	0.1	0.1	0	0
Eastern U.S.A. Contri. bution	MOE	82.2	74.2	63.8	44.1	74.9	53.6	75.4	96.4	99.1
	AES	78.5	69.6	46.4	43.1	58.4	45.1	68.1	95.7	99.7
Total Canadian Contri. bution	MOE	17.8	25.0	36.4	56.2	24.7	46.5	24.6	3.4	0.7
	AES	21.4	30.3	53.3	57.2	41.5	54.6	31.8	4.3	0.3

Table A8-12 Transfer Matrix of:

Percent Contribution to Annual Sulfate Concentration

		Receptor Areas								
Source Regions	Models	B.Waters (1)	Alg. (2)	Musk. (3)	Que. (4)	S. N.Sc. (5)	Vt. NH. (6)	Adir. (7)	Penn. (8)	Smokies (10)
1 Mich.	MOE	7.5	9.6	12.0	7.7	7.1	8.5	10.2	9.3	3.1
	AES	9.0	12.6	21.5	14.5	8.6	12.2	10.7	10.0	1.8
2 Ill. Ind.	MOE	25.0	24.6	20.6	14.2	13.2	14.8	16.7	19.5	27.9
	AES	3.6	20.3	9.4	6.4	4.0	6.6	7.7	9.0	18.6
3 Ohio	MOE	13.8	13.6	14.3	12.3	13.9	14.1	16.1	23.7	11.7
	AES	0	2.9	16.7	10.5	14.1	15.2	17.9	35.8	11.0
4 Penn.	MOE	6.2	5.9	6.3	6.8	9.0	8.0	8.9	16.7	3.7
	AES	0	0.9	3.6	5.4	6.7	8.0	11.0	16.9	0.8
5 N.York to Maine	MOE	5.0	4.1	4.7	7.7	16.5	9.4	9.3	2.9	2.2
	AES	0.9	2.6	3.1	9.9	28.6	10.3	9.9	1.4	0.1
6 Kent. Tenn.	MOE	7.5	6.4	5.5	4.6	4.7	4.7	5.1	6.4	25.8
	AES	0	1.4	2.0	0.3	1.2	1.3	1.9	5.2	27.7
7 W.Virg. to N.C.	MOE	7.5	7.3	7.1	8.0	11.1	8.9	9.3	10.0	7.1
	AES	0	0	1.1	1.6	3.1	3.3	3.9	7.1	6.5
8 Rest of (USA) Fld to Mo. to Minn.	MOE	13.7	14.6	9.3	6.5	5.2	6.1	6.6	5.9	16.0
	AES	39.6	28.6	8.8	4.8	3.2	4.4	5.7	6.9	32.3
9 Ontario	MOE	8.8	9.6	16.4	18.5	10.6	14.8	13.1	4.3	1.8
	AES	4.5	18.9	27.5	26.3	14.9	21.9	21.9	6.8	0.8
10 Quebec	MOE	5.0	3.6	3.5	13.2	7.3	10.3	4.2	1.1	0.9
	AES	6.3	6.3	5.3	17.7	12.0	15.4	8.8	0.6	0.2
11 Atlantic Provinces	MOE	0	0.5	0.3	0.6	1.4	0.5	0.4	0.1	0
	AES	0	0	0	0.8	2.5	0.2	0.1	0	0
Western Canada	AES	36.0	5.7	1.0	1.8	1.1	1.0	0.5	0.2	0
Eastern U.S.A. Contri. bution	MOE	86.2	86.1	79.8	67.8	80.7	74.5	82.2	94.4	97.5
	AES	53.1	69.3	66.2	53.4	69.5	61.3	68.7	92.3	98.8
Total Canadian Contri. bution	MOE	13.8	13.7	20.2	32.3	19.3	25.6	17.7	5.5	2.7
	AES	46.8	30.9	33.8	46.7	30.5	38.5	31.3	7.6	1.0

Table A8-13 Transfer Matrix of:

Percent Contribution to Annual Sulfur Dry Deposition

		Receptor Areas								
Source Regions	Models	B.Waters (1)	Alg. (2)	Musk. (3)	Que. (4)	S. N.Sc. (5)	Vt. NH. (6)	Adir. (7)	Penn. (8)	Smokies (10)
1 Mich.	MOE	8.3	12.6	15.5	6.4	6.0	7.2	10.8	8.7	1.3
	AES	4.2	26.2	17.6	9.2	2.9	6.3	7.5	6.1	0.4
2 Ill. Ind.	MOE	21.7	20.0	14.0	8.0	7.8	8.0	10.9	11.3	20.7
	AES	8.3	14.3	5.9	4.0	1.9	2.8	4.4	4.1	10.8
3 Ohio	MOE	13.3	10.0	11.4	8.2	10.6	9.7	13.9	27.0	7.5
	AES	0	3.6	11.2	9.2	6.8	10.5	16.8	35.8	6.2
4 Penn.	MOE	5.0	4.0	5.2	4.8	8.3	6.4	9.3	31.7	1.6
	AES	0	1.2	2.9	5.3	3.9	7.7	11.8	36.4	0.4
5 N.York to Maine	MOE	3.3	2.6	4.2	7.4	28.3	11.9	16.3	2.4	0.6
	AES	0	1.2	2.9	11.8	39.8	14.0	19.9	1.2	0
6 Kent. Tenn.	MOE	5.0	3.5	2.6	2.0	2.5	2.0	2.6	3.1	40.2
	AES	0	1.2	1.5	0	1.0	0.7	1.9	3.1	41.5
7 W.Virg. to N.C.	MOE	5.0	4.0	4.4	4.8	9.1	5.7	7.3	9.6	4.5
	AES	0	0	1.0	2.6	1.9	2.8	3.7	6.1	3.5
8 Rest of (USA) Fld to Mo. to Minn.	MOE	20.0	18.6	7.5	3.8	3.0	3.4	4.3	2.6	23.3
	AES	66.7	22.6	4.4	2.6	1.0	1.4	2.5	2.9	36.5
9 Ontario	MOE	13.3	20.4	31.0	26.0	11.0	17.7	18.6	3.0	0.5
	AES	3.8	23.8	47.8	18.4	6.8	15.4	21.1	4.1	0.4
10 Quebec	MOE	5.0	4.1	3.8	28.0	10.0	27.8	5.9	0.4	0.1
	AES	0	4.8	4.4	36.8	9.7	38.5	10.6	0.2	0
11 Atlantic Provinces	MOE	0	0	0.1	0.8	3.6	0.5	0.2	0	0
	AES	0	0	0	1.3	24.3	0	0	0	0
Western Canada	AES	16.7	1.1	0.4	0	0	0	0	0	0
Eastern U.S.A. Contribution	MOE	81.6	75.3	64.8	45.4	75.6	54.3	75.4	96.4	99.7
	AES	79.2	70.3	47.4	44.7	59.2	46.2	68.5	95.7	99.3
Total Canadian Contribution	MOE	18.3	24.5	34.9	54.8	24.6	46.0	24.7	3.4	0.6
	AES	20.5	29.7	52.6	56.5	40.8	53.9	31.7	4.3	0.4

Table A8-14 Transfer Matrix of:

Percent Contribution to Annual Sulfur Wet Deposition

		Receptor Areas								
Source Regions	Models	B.Waters (1)	Alg. (2)	Musk. (3)	Que. (4)	S. N.Sc. (5)	Vt. NH. (6)	Adir. (7)	Penn. (8)	Smokies (10)
1 Mich.	MOE	8.1	11.5	14.3	6.7	6.2	7.5	10.6	8.6	1.7
	AES	13.3	22.1	17.6	11.1	5.1	5.3	7.0	5.1	1.2
2 Ill. Ind.	MOE	24.2	21.5	15.9	10.0	9.6	9.9	12.5	12.5	22.3
	AES	6.7	23.1	12.5	6.7	3.4	3.8	4.5	6.6	9.0
3 Ohio	MOE	12.9	11.1	12.3	9.5	11.6	10.7	14.8	26.3	8.3
	AES	0	5.8	25.0	12.2	8.5	18.3	20.4	33.7	3.6
4 Penn.	MOE	4.8	4.5	5.5	5.4	8.5	6.8	9.2	29.6	2.1
	AES	0	2.9	7.4	7.8	5.1	13.7	14.7	24.2	0.6
5 N.York to Maine	MOE	4.8	3.3	4.3	7.4	25.0	10.9	14.4	2.5	1.1
	AES	0	1.9	3.4	17.8	40.7	20.6	18.5	1.5	0
6 Kent. Tenn.	MOE	6.5	4.5	3.3	2.8	3.3	2.7	2.3	3.6	37.1
	AES	0	1.9	5.7	1.1	1.7	2.3	3.8	6.3	26.4
7 W.Virg. to N.C.	MOE	6.5	4.8	5.1	5.6	9.8	6.5	7.9	9.9	5.0
	AES	0	0	2.3	4.4	5.1	8.4	8.9	12.8	3.6
8 Rest of (USA) Fld to Mo. to Minn.	MOE	16.1	17.1	8.0	4.6	3.7	4.1	4.9	3.1	20.4
	-AES	60.0	22.1	5.1	2.2	1.7	2.3	3.2	6.0	55.1
9 Ontario	MOE	11.3	17.0	27.4	24.1	10.8	16.5	17.5	3.2	0.9
	AES	6.7	17.3	18.8	18.9	10.0	12.2	12.7	3.6	0
10 Quebec	MOE	4.8	4.1	3.7	23.1	8.9	23.7	5.6	0.5	0.4
	AES	0	1.0	1.7	16.7	8.5	13.0	5.1	0.3	0
11 Atlantic Provinces	MOE	0	0.4	0.2	0.8	2.9	0.5	0.3	0.1	0
	AES	0	0	0	1.1	10.2	0	0	0	0
Western Canada	AES	13.3	1.9	0.5	0	0	0	1.2	0	0
Eastern U.S.A. Contribution	MOE	83.9	78.3	68.7	52.0	77.7	59.1	76.6	96.1	98.0
	AES	80.0	79.8	79.0	63.3	71.3	74.7	81.0	96.2	99.5
Total Canadian Contribution.	MOE	16.1	21.5	31.3	48.0	22.6	40.7	23.4	3.8	1.3
	AES	20.0	20.2	21.0	36.7	28.7	25.2	19.0	3.9	0

Table A8-15 Transfer Matrix of:

Percent Contribution to Total Annual Sulfur Deposition

		Receptor Areas								
Source Regions	Models	B.Waters (1)	Alg. (2)	Musk. (3)	Que. (4)	S. N.Sc. (5)	Vt. NH. (6)	Adir. (7)	Penn. (8)	Smokies (10)
1 Mich.	MOE	8.2	12.2	14.7	6.5	6.1	7.2	10.7	8.9	1.5
	AES	7.7	23.9	17.6	10.2	3.7	5.8	6.9	5.7	0.7
2 Ill. Ind.	MOE	23.0	21.1	14.8	8.7	8.7	8.7	11.4	11.8	21.5
	AES	7.7	18.6	8.9	4.8	2.4	3.3	4.4	5.1	10.1
3 Ohio	MOE	13.1	10.5	11.5	8.6	11.1	10.1	14.8	26.6	7.7
	AES	0	4.8	17.6	10.8	7.3	14.2	18.6	35.0	5.2
4 Penn.	MOE	4.9	4.2	5.3	5.1	8.5	6.5	9.4	30.8	1.8
	AES	0	2.1	5.0	7.2	4.3	10.2	13.5	31.4	0.5
5 N.York to Maine	MOE	4.1	2.9	4.2	7.4	26.0	11.6	15.4	2.4	0.8
	AES	0	2.1	3.2	15.0	39.9	17.1	19.2	1.2	0
6 Kent. Tenn.	MOE	5.7	3.7	2.9	2.3	2.9	2.4	2.9	3.4	38.5
	AES	0	1.6	3.4	0.6	1.2	1.5	2.8	4.4	35.6
7 W.Virg. to N.C.	MOE	6.6	4.4	4.6	5.1	9.3	6.0	7.4	9.7	4.8
	AES	0	0.5	1.3	3.6	3.0	5.5	6.3	8.8	3.5
8 Rest of (USA) Fld to Mo. to Minn.	MOE	18.0	17.8	7.7	4.1	3.4	3.7	4.5	2.9	22.3
	AES	64.1	22.3	4.7	2.4	1.8	1.8	2.8	4.1	43.8
9 Ontario	MOE	11.5	19.5	30.3	25.8	11.1	17.4	17.4	3.1	0.7
	AES	2.6	20.7	34.7	18.6	8.0	13.9	17.0	3.8	0.2
10 Quebec	MOE	4.9	4.0	3.8	25.8	9.3	26.1	5.8	0.4	0.2
	AES	2.6	2.6	3.2	25.8	9.2	26.3	7.9	0.2	0
11 Atlantic Provinces	MOE	0	0.1	0.1	0.8	3.3	0.5	0.3	0	0
	AES	0	0	0	0.6	19.6	0.4	0	0	0
Western Canada	AES	15.3	1.0	0.5	0	0	0	0.6	0	0
Eastern U.S.A. Contribution	MOE	83.6	76.8	65.7	47.8	76.0	56.2	76.5	96.5	98.9
	AES	79.5	75.9	61.7	54.6	63.6	59.4	74.5	95.7	99.4
Total Canadian Contribution	MOE	16.4	23.6	34.2	52.4	23.7	44.0	23.5	3.5	0.9
	AES	20.5	24.3	38.4	45.0	36.8	40.6	25.5	4.0	0.2

Appendix 9

Workshop Summary Reports:

Atmospheric and Science Reviews

Modeling Evaluation and Intercomparison

(16-17 December 1980, Washington, D.C.)

Atmospheric Science Review

At a Work Group 2 workshop meeting held in Washington, DC on December 16, 1980, a wide-ranging discussion occurred regarding the most important areas in the atmospheric sciences which were closely connected with the use of long range transport models. From that discussion emerged several topics on which Work Group 2 would prepare reviews for their May 15, 1981, Phase II report. The purpose of these reviews would be to highlight the state of knowledge in the particular topic areas, and to indicate how that knowledge is reflected in various models being used by this Work Group. The reviews are to be brief, comprehensive, reflect recent literature and work in progress, and written in a manner which is comprehensible to the educated layman.

The initial topics chosen are described briefly below, and the lead authors are identified. First drafts of the write-ups will be distributed to all Work Group 2 members for discussion in the last half of February, 1981.

1) Sulfur and Nitrogen Chemistry in LRT Models

(A.P. Altshuller) Homogeneous and heterogeneous reaction mechanisms will be reviewed. The degree to which models can treat sulphur chemistry as being first-order and independent of other atmospheric cycles (e.g., oxidants, nitrogen, particulates, visibility) will be discussed. Seasonal differences will be mentioned. The ways in which SO_2 is converted into sulphuric acid, as opposed to other sulfate products, will be emphasized in all parts of the report.

It is known that nitrogen chemistry is more complex than sulphur chemistry, and that in many situations it is not first-order. Additionally, other key species involved in nitrogen chemistry are often not being measured. This discussion will review the above issues, as well as the aspects mentioned above for sulfur. Finally, the possibility of crudely modeling nitrogen reactions in a pseudo first order way in existing Lagrangian models will be discussed.

2) Trends in precipitation composition and deposition (J. Miller) What data sets are available which have not been discussed to date? Are the data sets reliable? Is there any way to relate trends, which these and newer sets of data may show, to estimates of past and present emissions of SO_2; should the comparison even be made in view of the different spatial distribution of the sources, the different release heights of the SO_2, etc.

3) Deposition processes for sulphur and nitrogen compounds (G. Van Volkenburg) Once atmospheric reactions have occurred, how does one measure and model the various pathways of deposition, both wet and dry? Are the mechanisms and amounts of deposition radically different because of seasonal changes? What is the role of changing

meteorological conditions (e.g., mixing height, temperature, type of storm, amount of precipitation) and surface conditions (wet, snow-covered, vegetation-covered, etc.)? How valid are the parameterigation of deposition being used in models currently?

4) Global and western North American measurements of precipitation pH (P. Summers) The strength of the assumption of "unpolluted" rain having a pH of 5.6 will be compared to recent global background measurements, and these measurements will be interpreted in light of current assumptions about residence times of acid precursor compounds and scavenging mechanisms for these compounds over oceans, coastal regions, and over land. Recent measurements from western North America will be examined thoroughly.

2. Evaluation and Intercomparison of Selected Models

On December 17, 1980, the first workshop of Group 2 was convened to plan a comprehensive model evaluation and intercomparison program for the five-month period up to May 1981. The follwing items wre agreed upon:

1) Management: J.W.S. Young and B. Niemann were appointed as the Canadian and U.S. "whips", respectively, to insure that, to the maximum extent possible, data, manpower, and funding would be made available for this exercise by the various agencies involved.

Agreement was reached among EPA (US), and AES and OME (Canada) that if required, support for a contractor to assist in assembling data sets would be made available.

2) Task scheduling: Once tasks had been outlined and agreed to, it was agreed that the sponsoring agencies would hold workshops to discuss progress on the tasks, at approximately monthly intervals. The second workshop was scheduled for January 13-14, 1981 in Washington, and the third for the last half of February in Toronto.

3) Provision of an "Agreed", "Unified" North American Sulfur Inventory: The crucial need for a current, unified sulfur inventory for North America was raised again. It is understood that Work Group 3B is responsible for the provision of this inventory. It is to be published as a

tabulation, identifying for each point and area source: location, most recent annual and seasonal emissions, and other stack paramenters (where appropriate). Using the inventory breakouts of emissions totals for point and area sources will be undertaken for various georgraphical regions, including continental, country, the 11 Canadian source regions, the SURE approximations to states and provinces, and the 63 SURE source regions.

4) Meteorological Year for Test Use: 1978 was chosen. Annual, winter (Jan.-March), summer (July-September), and monthly slices from seasons (January and July) will be used.

5) Meteorological Year for Greneral Use: To be decided at second workshop. P. Summers will produce notes for discussion.

6) Input data sets for testing: The 1978 data sets from CANSAP, MAP3S, SURE, Ontario Hydro, and SAROAD archives will be employed.

7) Parameters to be modeled for sulphur: Wet deposition, and SO_2 and SO_4 concentrations will be the three primary outputs. Estimates of dry and total deposition are of lower priority because they can not be validated against field observations and they are, therefore, more uncertain.

8) Methods of Parameterization: A. Venkatram and J. Shannon will write a position paper for the January 13-14 workshop to stimulate discussion on which, and how, parameters should be "tuned" to data sets. Can statistics be generated from this exercise which say anything about the confidence of the models?

9) Methods of Validation: A. Venkatram will prepare, for the January workshop, a position paper for discussion which indicates how the models can be validated in a uniform manner, and how the measure of validity can be expressed from model to model in a uniform manner.

10) Amount of Model "Production Usage": The chairman of Work Group 2 will extract from the chairmen of Work Group 3B the number of "full scenarios" to be run in Phase II. This number, along with estimates of model usage for validation and intercomparison, will identify the level of effort required by each modeler.